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Results of Holdover Time Testing of Type IV Anti-Icing Fluids With the Improved NCAR Artificial Snow Generation System

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Final Report

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16. Abstract

This report discusses improvements to the National Center for Atmospheric Research (NCAR) artificial snow generation machine and the results of anti-icing fluid testing with the improved machine. The improvements include (1) improved control of snowfall rate, (2) development of an integrated frosticator plate/snow mass measuring system, (3) automatic control and recording of the experiment, and (4) direct control of the frosticator plate temperature through an area heater controlled by an interface unit.

This improved machine was used to conduct anti-icing fluid holdover time tests on several Type IV fluids. The results showed the typical inverse relationship between holdover time and snowfall rate. The results from the improved machine were compared to previous natural and artificial snow tests conducted by the University of Quebec at Chicoutimi and NCAR and showed good agreement in general.

Tests with varying snowfall rates showed a factor of 1.5 to 2.0 longer holdover time for nonconstant snowfall rates. This result suggests that natural snow conditions are not as severe as the constant snowfall rate conditions tested in the laboratory. Causes for the longer holdover time were suggested to be (1) the longer time available for the absorption of the melted snow water and (2) the warmer temperatures experienced during the time varying rate tests as compared to the constant rate tests.

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EXECUTIVE SUMMARY

This report discusses improvements to the National Center for Atmospheric Research (NCAR) artificial snow generation machine and the results of anti-icing fluid testing with the improved machine. The improvements include (1) improved control of snowfall rate using a digital stepper motor controlled by LabView software running on a notebook PC, (2) development of an integrated frosticator plate/snow mass measuring system that allows the accurate determination of snowfall rate every 1.5 seconds by direct measurement of the weight of snow on the plate being tested, (3) automatic control and recording of the experiment by LabView software running on a notebook PC, (4) installation of a temperature sensor in the frosticator plate whose output is recorded every 5 seconds on the PC, (5) addition of a cylindrical guide near the drill bit to allow for an extended length of the ice core for longer experiments, and (6) direct control of the frosticator plate temperature through an area heater controlled by an interface box.

This improved machine was used to conduct anti-icing fluid tests on the following Type IV fluids: UCAR Ultra+, Kilfrost ABC-S, Octagon Maxflight, SPCA AD-480, and Clariant Safewing MP IV. The results showed the typical inverse relationship between holdover time and snowfall rate.

The results from the machine were compared to previous natural and artificial snow tests conducted by the University of Quebec at Chicoutimi and NCAR and showed good agreement in general. The NCAR natural snow tests had holdover times a factor of two shorter than the artificial snow tests from the new machine. These results may be attributed to more rapid cooling of the frosticator plate for the natural snow tests than during the artificial snow tests with the machine.

An important new result from this study is the cooling of the frosticator plate by the release of latent heat during the melting of snow. The plate cooling rate was shown to be proportional to the snowfall rate from both direct plate temperature measurements and theoretical considerations. Holdover times for Type IV fluids were shown to be significantly shorter when the plate temperature was allowed to cool freely as opposed to being maintained at a constant temperature. This was attributed to the cooler plate temperature for the freely cooling plate as a result of snow melting.

Tests with varying snowfall rates showed a factor of 1.5 to 2.0 longer holdover time for nonconstant snowfall rates. This result suggests that natural snow conditions are not as severe as the constant snowfall rate conditions tested in the laboratory. Causes for the longer holdover time were suggested to be (1) the longer time available for the absorption of the melted snow water and (2) the warmer temperatures experienced during the time varying rate tests as compared to the constant rate tests.

1. INTRODUCTION.

Current methods of establishing holdover times for deicing/anti-icing fluids under snow conditions involve outdoor testing using frosticator plates during snow storms. While providing data on the performance of a particular fluid under actual snow conditions, this approach to testing can only be done during winter snow conditions, requiring considerable effort and expense. In addition, outdoor conditions are often highly variable with quantities such as wind speed and direction, temperature, and snowfall intensity changing rapidly. Thus, it is often difficult to compare tests from a particular snowstorm with tests conducted during other snowstorms, and even within the same storm, since exact conditions of snow intensity, wind speed and direction, and temperature are seldom duplicated. In contrast to outdoor testing, indoor testing in a cold room provides a well-controlled environment in terms of temperature and wind (calm) and offers the opportunity of conducting testing year round. It also offers the opportunity of repeating tests to establish reliability and error tolerance limits and to develop functional relationships between variables by varying only one at a time. The current problem preventing cold room testing of deicing/anti-icing fluids in cold rooms is the lack of an appropriate method to generate realistic snow in sufficient quantities to perform the tests. Recent studies by the University of Quebec at Chicoutimi (UQAC) have used ice formed by the freezing of 300-micron drops on a cold surface to perform indoor testing in a cold room.

A new method of artificial snow generation by mechanically shaving an ice core was developed by Rasmussen et al. (1999). The system is capable of producing a uniform snow rate over a 30- by 50-cm test panel for periods of up to 2 hours, depending on the snowfall rate. Holdover time tests using Ultra+ Type IV anti-icing fluid were conducted and compared to previous outdoor and indoor tests of this same fluid type. The artificial snow results were shown to give a holdover time to snowfall rate relationship for Ultra+ similar to previous studies at UQAC and at NCAR. However, the artificial snow results were shown to be consistently shorter than UQAC by 10% - 20%. It was hypothesized that the method of snow application used by UQAC in which snow was alternately applied for 1 minute and not applied for 2 minutes may have resulted in longer holdover times for the UQAC experiments than in the Rasmussen et al. (1999) results. However, only one fluid type and concentration was tested and in order to make more definitive statements more tests are required with different types and concentrations of deicing/anti-icing fluids.

Another possible source for error is whether the artificial snow tests accurately represented the effect of natural snow on deicing/anti-icing fluids. Comparison of the snow machine holdover panel tests with natural snow tests are desirable in order to evaluate the appropriateness of the artificial snow to simulate natural snow tests.

A number of desired improvements to the system were identified. These included (1) a snowfall rate that did not increase with time, (2) the ability to measure the actual snowfall rate that the test panel is experiencing, (3) a method to control the experiment and record the data every few seconds with a computer, (4) the ability to record the temperature of the plate during the experiments, (5) an extended length of the ice core to allow for longer experiments; and (6) control of the frosticator plate temperature.

In the following section a number of improvements made to the original snow machine are presented. Frosticator plate tests with natural snow falling into a cold room are presented in section 3. Results from tests on a variety of fluid types and concentrations are made in section 4, as well as a comparison to UQAC indoor and outdoor tests and the natural snow tests in the NCAR cold room. An analysis of the effect of snowfall rate on the plate temperature is presented in section 5. In section 6 results related to the effect of plate temperature on holdover time are presented. Section 7 includes a discussion of trends related to the total snow mass required to cause fluid failure. The effect of variable snowfall rates on holdover time is presented in section 8. A summary and concluding remarks as well as suggestions for future tests are made in section 9.

2. IMPROVEMENTS TO ARTIFICIAL SNOW GENERATION SYSTEM.

This section discusses the following improvements made to the original system: (1) improved control of snowfall rate in time, (2) method to measure the actual snowfall rate falling on the test panel, (3) method to control the experiment and record the data every few seconds with a computer, (4) ability to record the temperature of the plate during the experiments, (5) ability to run longer experiments by extending the length of the ice cores, and (6) ability to control the frosticator plate temperature.

2.1 IMPROVED CONTROL OF THE SNOWFALL RATE IN TIME.

The previous system used a direct current (DC) motor controlled by a power supply to drive the translator and ice core into the rotating drill bit. The resulting snowfall rate was found to increase in time (figure 1). It was determined that over time the motor warmed up and ran faster, resulting in an increased snowfall rate. In order to overcome this problem, the DC motor was replaced with a digitally controlled stepper motor, as shown in figure 2. The stepper motor was controlled by LabView version 5.0 software and resulted in snowfall rates that could be maintained constant in time (figure 3) or variable in time as specified in software (figure 4).

2.2 METHOD TO MEASURE THE ACTUAL SNOWFALL RATE FALLING ON THE TEST PANEL.

The previous NCAR indoor tests with the original snow machine (Rasmussen et al., 1999) determined the snowfall rate by measuring the rate 5 minutes before and after each panel test. This method assumed that the rate during the actual test varied linearly between these two rates. In order to improve the measurement of snowfall rate, we designed a new panel test system that could be placed on a digital balance and weighed in real time during the snow event. The fluid from the test was entirely contained by the system as well. Thus, any change in mass was therefore directly proportional to the snowfall rate. Figure 5 shows a side view of the new test panel system positioned on top of the balance. In the upper left of the photo is a temperature probe used to measure the temperature of the plate during tests. The digital balance underneath measures the total weight of the system up to 6000 g with a resolution of 0.1 g. A top view of the system (figure 6) shows that the overall dimensions of the system are only slightly larger than

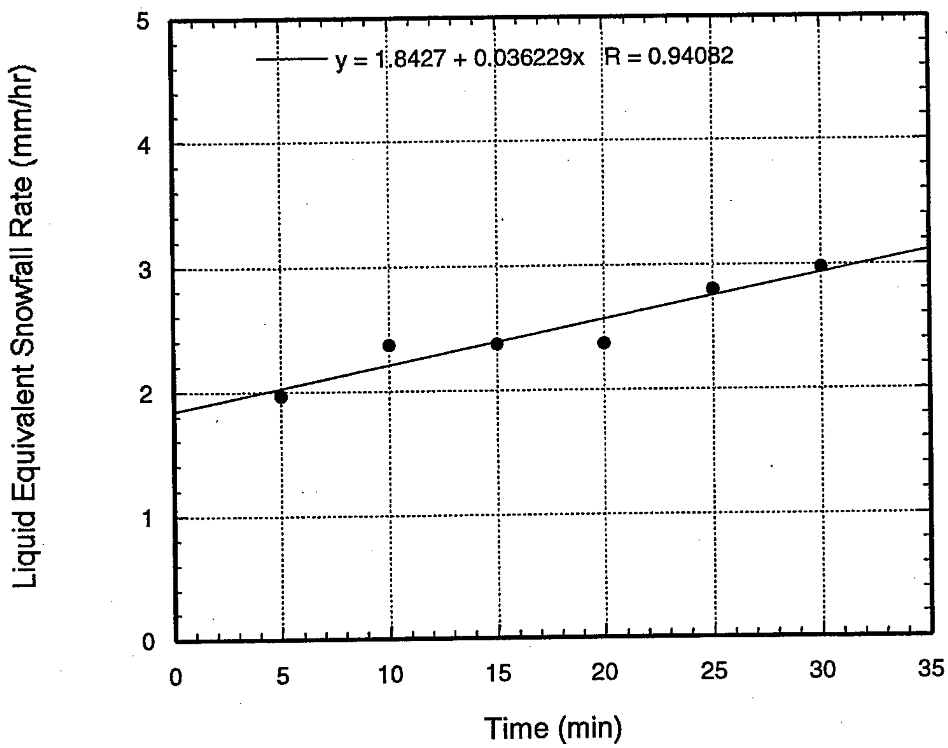

FIGURE 1. SNOWFALL RATE FROM PREVIOUS SNOW GENERATION SYSTEM

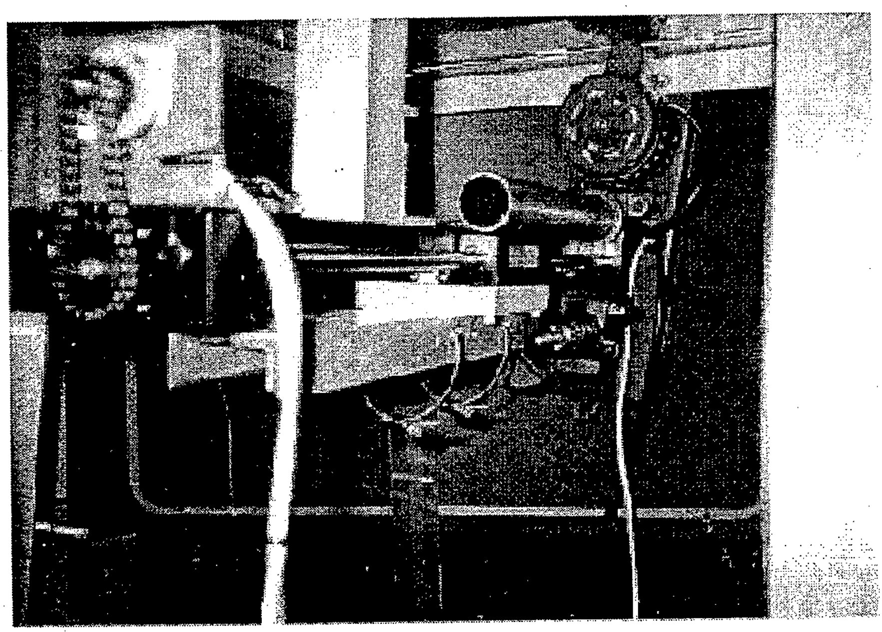

FIGURE 2. PHOTOGRAPH OF STEPPER MOTOR AND TRANSLATION STAGE

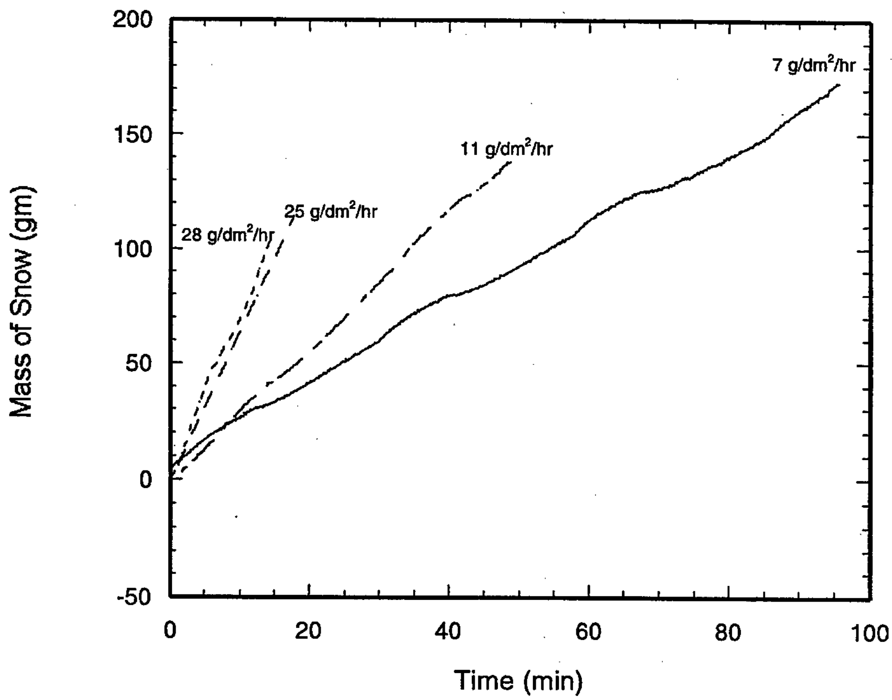

FIGURE 3. TIME SERIES OF SNOW MASS FOR VARIOUS SNOWFALL RATES

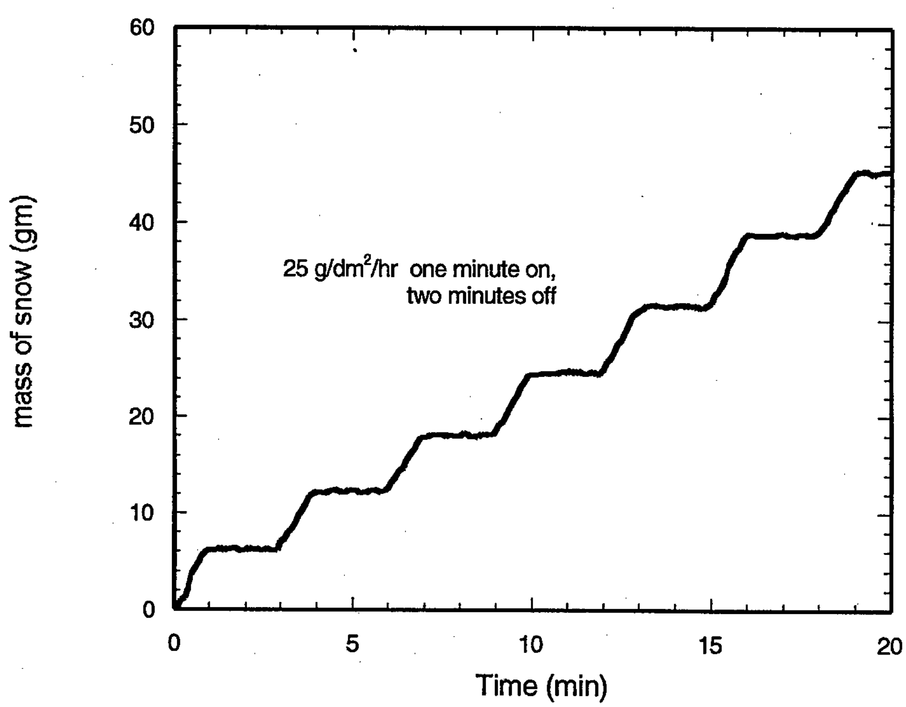

FIGURE 4. TIME SERIES OF SNOW MASS FOR A TEST WITH RATE ON FOR 1 MINUTE AND OFF FOR 2 MINUTES

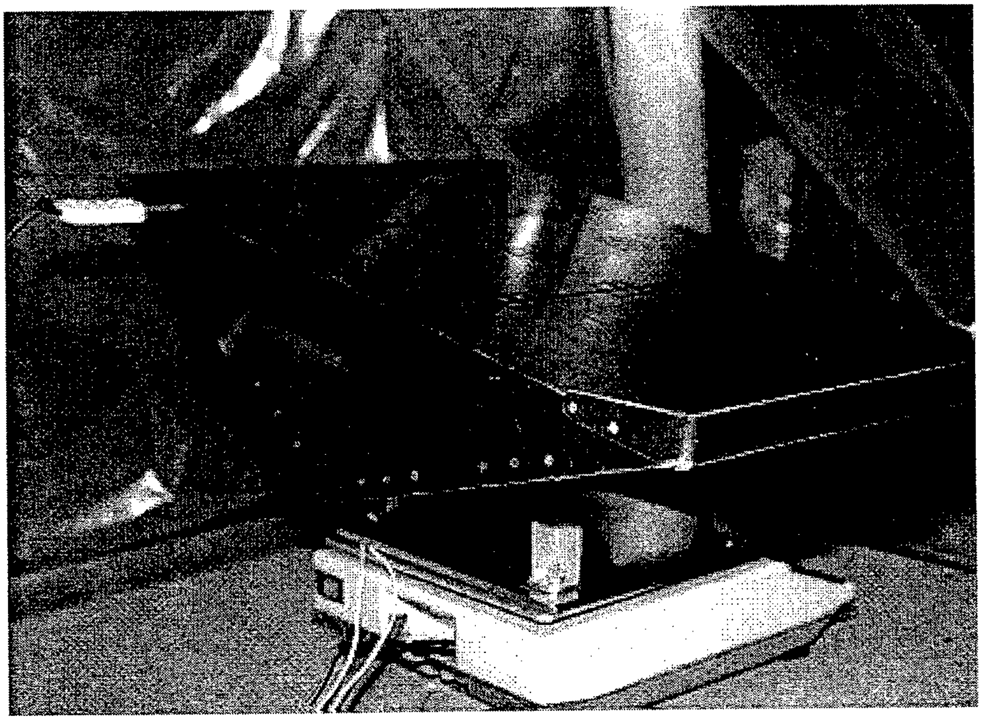

FIGURE 5. PHOTOGRAPH OF NEW, SELF-CONTAINED FROSTICATOR PLATE TEST SYSTEM

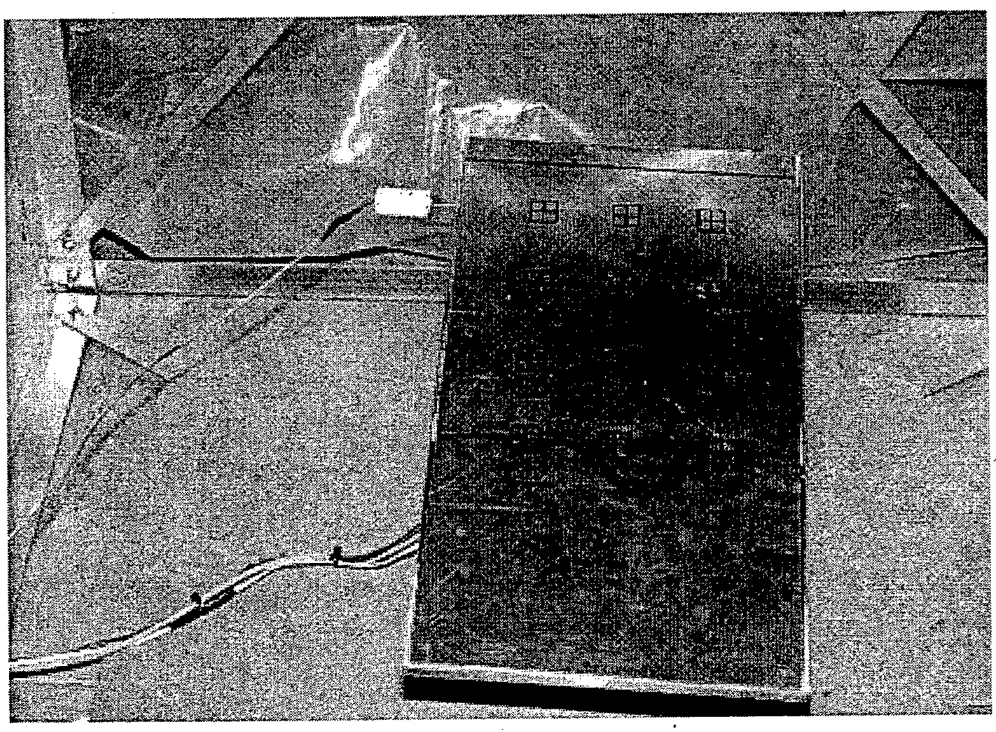

FIGURE 6. TOP VIEW OF NEW, SELF-CONTAINED FROSTICATOR PLATE TEST SYSTEM

the 30- x 50-cm^2 plate dimensions. Also evident in this photo are the cables for the temperature probe and the digital scale. Figure 7 shows the system with the test panel removed and inverted. The rectangular area is a thermal heater (Minco silicone area heater, 2 W/in^2) applied to the back of the test panel and used in conjunction with an Omega temperature controller to control the temperature of the plate if so desired. The temperature of the plate can be controlled to +/- 0.25°C by this method.

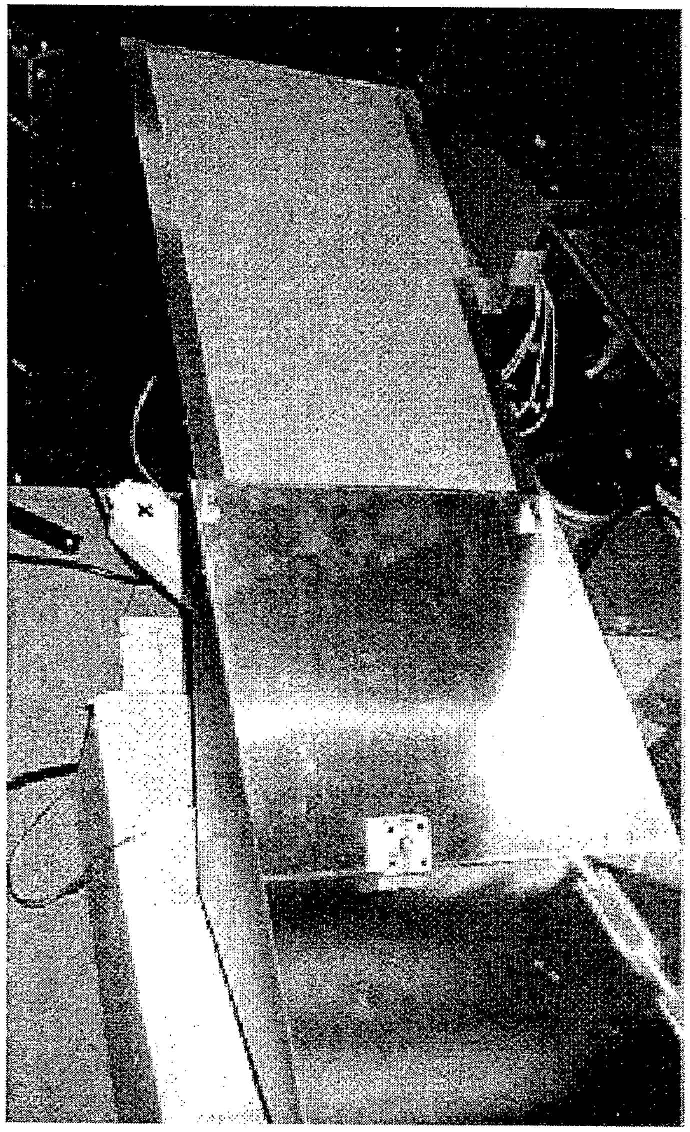

FIGURE 7. TOP VIEW OF FROSTICATOR PLATE TEST SYSTEM WITH THE TOP PLATE REMOVED TO SHOW THE HEATER PAD

At the start of an experiment fluid is poured onto the plate starting with the upper portion and allowed to run down as usual. Any excess fluid over the side and end of the plate is retained inside the hollow inner chamber of the system and does not affect the total weight of the system plus fluid. This is also true during the test as well. Any snow that falls on top of the plate is then weighed in real time by the digital balance.

2.3 METHOD TO CONTROL THE EXPERIMENT AND MEASURE THE SNOWFALL RATE EVERY FEW SECONDS WITH A COMPUTER.

Data from the original NCAR snow machine tests were recorded manually at the start and end of each experiment. In order to monitor the snowfall rate every few seconds, as well as the temperature of the plate and the room, the data collection was automated using a notebook PC computer running LabView 5.0 data acquisition and control software. Integral to the system is an electronic interface unit which provides connections between the experiment and the PC. The interface unit houses the stepper motor driver circuitry and signal conditioning for the RTD (Resistive Temperature Device) and the Omega temperature controller for the plate.

A schematic of the system is shown in figure 8. As indicated, the interface box controls the heater and the stepper motor on/off and speed as well as the on/off of the drill motor. Both the PC and interface box are located in a room adjacent to the cold room maintained at room temperature. A second monitor, keyboard, and mouse are located in the cold room to allow the operator control adjacent to the experiment. This is important in order to start the test just after application of the fluid and to end the test shortly after failure is called. At the end of the experiment, information on the fluid type and concentration, experiment number and date, and any other comments can be entered directly into the file. Each experiment is automatically named by the date and time of the experiment. A separate manual log of each experiment is maintained for backup purposes.

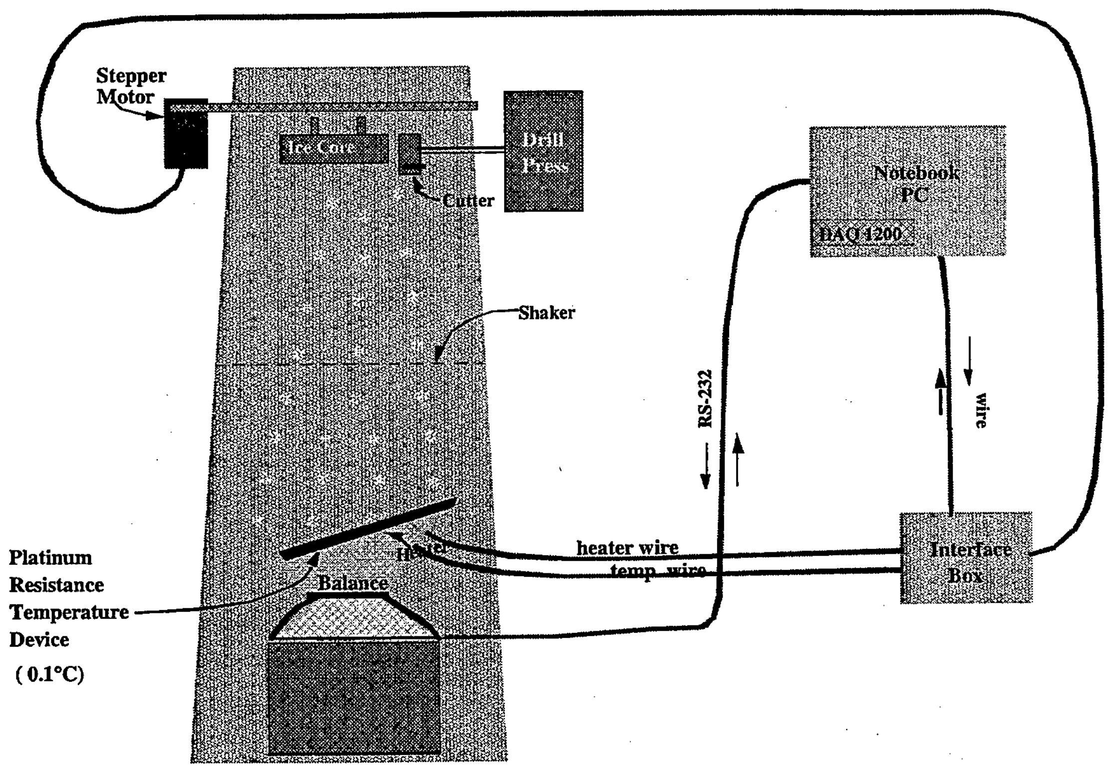

FIGURE 8. SCHEMATIC OF THE IMPROVED ARTIFICIAL SNOW GENERATION SYSTEM

2.4 ABILITY TO CONTROL THE TEMPERATURE OF THE PLATE AND RECORD ITS TEMPERATURE EVERY FEW SECONDS.

A key variable that is not routinely monitored in previous frosticator plate tests both indoors and outdoors is the plate temperature. In the new frosticator plate system described above we added the capability of measuring the temperature every 1.5 seconds during tests by measuring the plate temperature with a thin platinum RTD (Omega) temperature probe inserted directly into the thin part of the plate. This was accomplished by drilling a 1/8-in-diameter and 15-cm-long hole into the plate horizontally, 5 cm and 25 cm down from the top of the plate. The probe(s) is inserted into one or both of these holes. The resistance of the probe is monitored by software every 1.5 seconds and converted to a temperature. Thus, for every frosticator test we have a time series of plate temperature, as shown in figure 9. The current commercial temperature controller (Omega 76020) has only 6-bit resolution, limiting temperature resolution to 0.5°C. This will be improved in the future to have at least 0.1°C resolution.

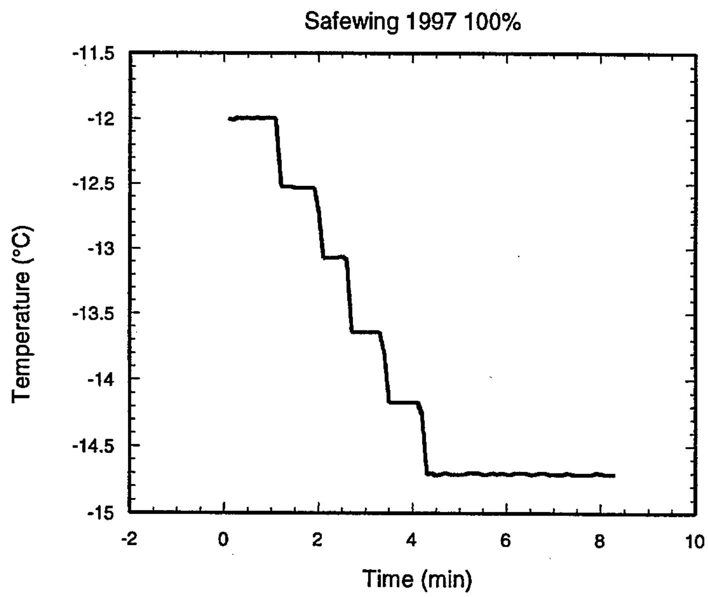

FIGURE 9. TIME SERIES OF TEMPERATURE FOR A TYPICAL FLUID TEST

2.5 ABILITY TO RUN LONGER EXPERIMENTS BY EXTENDING THE SIZE OF THE ICE CORE.

The ice core length of the original NCAR snow generation system was 44 cm. This limited the maximum time of snow generation to 30 minutes at 25 g/dm^2/hr, and 2 hours at 5 g/dm^2/hr. For warmer temperatures, longer sustained snow generation times are required. In order to increase the time of continuous snow generation, a guide for the ice cores was installed near the drill bit allowing ice cores as long as 66 cm to be used and extending the length of the tests at 25 g/dm^2/hr to 45 minutes, a 50% increase in time. In the future we may investigate using larger-diameter ice cores and wider drill bits as well as the possibility of backing up the ice core more rapidly and changing out the ice core in order to further extend the duration of snow tests.

3. NATURAL SNOW TESTS IN THE COLD ROOM.

During the winter of 97/98, indoor frosticator tests were performed with natural snow by opening up a hatch to the roof of the cold room, allowing natural snow to fall on a frosticator plate placed underneath. A 30- x 50-cm^2 collection pan was also placed next to the frosticator plate to estimate precipitation. The new snow collection system was not available during the winter season, requiring the use of the side by side snow measurement. The temperature of the tests was -10°C for all the tests described below. It was possible also to determine the density of the natural snow by measuring the depth and weight of the snow in the pan. The measured densities are shown in figure 10, as well as snow densities from the machine. As shown, the natural snow densities were between 0.05 to 0.12 g/cm^3 for the snowflakes which were moderately to heavily rimed and from 0.18 to 0.35 g/cm^3 for the snow pellets. The above range in snow density tends to be on the high side of natural snow densities and is likely due to the moderate to heavy riming observed. Typical snow densities range between 0.005 to 0.2 g/cm^3. The snow densities produced by the snow machine range between 0.02 to 0.06 g/cm^3 (figure 10) and represent dry snow conditions typically found in the atmosphere. As reported in our previous study (Rasmussen et al., 1999), the size distribution of the snowflakes is from 0.5 to 10 mm in diameter, consistent with observed snowflake sizes in nature.

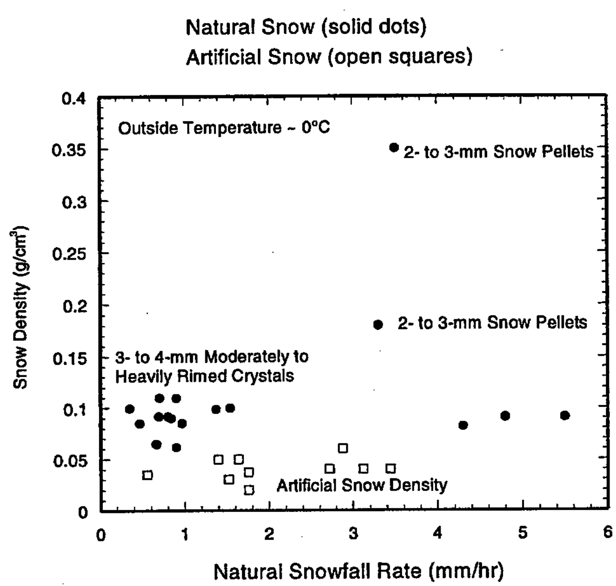

FIGURE 10. DENSITY OF NATURAL AND ARTIFICIAL SNOW AS A FUNCTION OF SNOWFALL RATE

Natural snow tests in the cold room at -10°C were conducted with Ultra+ 100%, Safewing 1957 100%, and Kilfrost ABC-S 100%, all Type IV fluids. Data from the tests are shown in table 1, with the holdover time, average precipitation rate, and precipitation type indicated. Individual plots of holdover time versus precipitation rate are shown in figure 11 for Ultra+, figure 12 for Safewing 1957, and figure 13 for Kilfrost ABC-S, all at 100%. All three figures have the same scale. The data for both the Ultra + and Safewing 1957 show good agreement with the inverse power law with little scatter. This likely reflects the lack of wind effects in the cold room and the

nearly constant temperature of -10°C. The Kilfrost data are especially interesting because of the high rates observed. The crystal types during these high rates was 2- to 4-mm light to moderately rimed single plates and dendrites.

TABLE 1. NATURAL SNOW TESTS IN COLD ROOM AT -10°C

Fluid Type	Concentration (%)	Precipitation Type	Snow Density (g/cm^3)	Snowfall Rate ($g/dm^2/hr$)	Holdover Time (min)
Ultra+	100	Heavily rimed 1- to 2-mm crystals	0.10	3.5	103.0
Ultra+	100	Heavily rimed 1- to 2-mm crystals	0.09	8.0	50.0
Ultra+	100	Heavily rimed 1- to 2-mm crystals	0.10	15.4	28.0
Ultra+	100	Heavily rimed 1- to 2-mm crystals	0.10	13.7	26.0
Ultra+	100	Heavily rimed 1- to 2-mm crystals	0.09	8.4	38.0
Safewing 1957	100	Heavily rimed 1- to 2-mm crystals	0.085	9.6	21.0
Safewing 1957	100	Heavily rimed 1- to 2-mm crystals	0.092	6.9	32.0
Safewing 1957	100	Heavily rimed 1- to 2-mm crystals	0.085	4.7	43.0
Safewing 1957	100	Moderate to heavily rimed 2- to 3-mm crystals	0.0622	9.0	25.0
Safewing 1957	100	One- to 3-mm light to moderately rimed crystals, some unrimed, dendrites	0.065	6.6	35.0
Safewing 1957	100	One- to 2-mm snow pellets	0.35	35.0	6.0
Kilfrost ABC-S	100	One- to 3-mm snow pellets	0.17	33.3	16.0
Kilfrost ABC-S	100	Heavily rimed 2- to 3-mm ice crystals	0.11	7.0	37.0
Kilfrost ABC-S	100	Moderately rimed 2- to 4-mm ice crystals	0.09	48.0	8.0
Kilfrost ABC-S	100	Lightly rimed 2- to 4-mm dendrites and plates	0.09	55.0	7.0
Kilfrost ABC-S	100	Lightly rimed 2- to 4-mm crystals	0.08	43.0	7.0
Kilfrost ABC-S	100	Moderately rimed 3- to 5-mm crystals	0.11	9.0	57.0

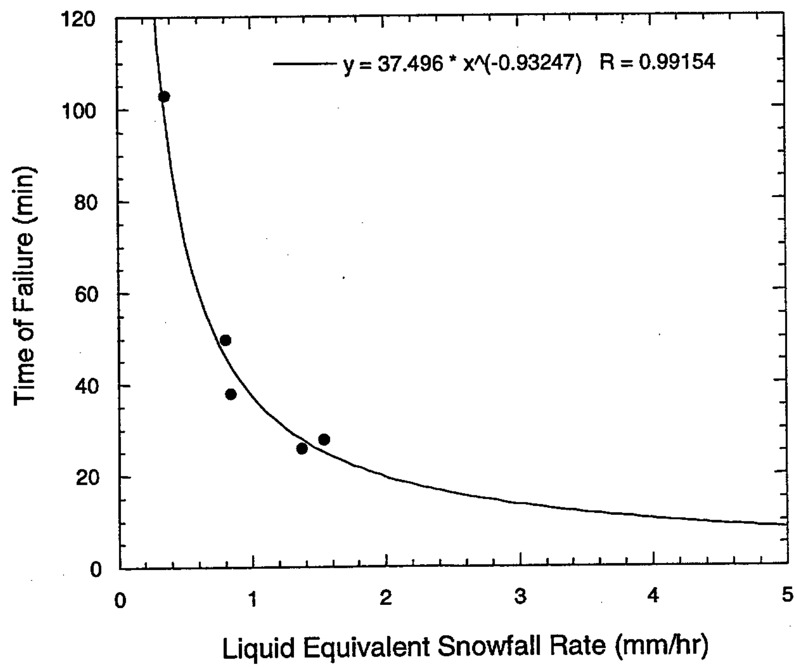

FIGURE 11. HOT VERSUS SNOWFALL RATE—NATURAL SNOW TESTS IN COLD ROOM OF ULTRA+ AT -10°C (PLATE TEMPERATURE FLOATING)

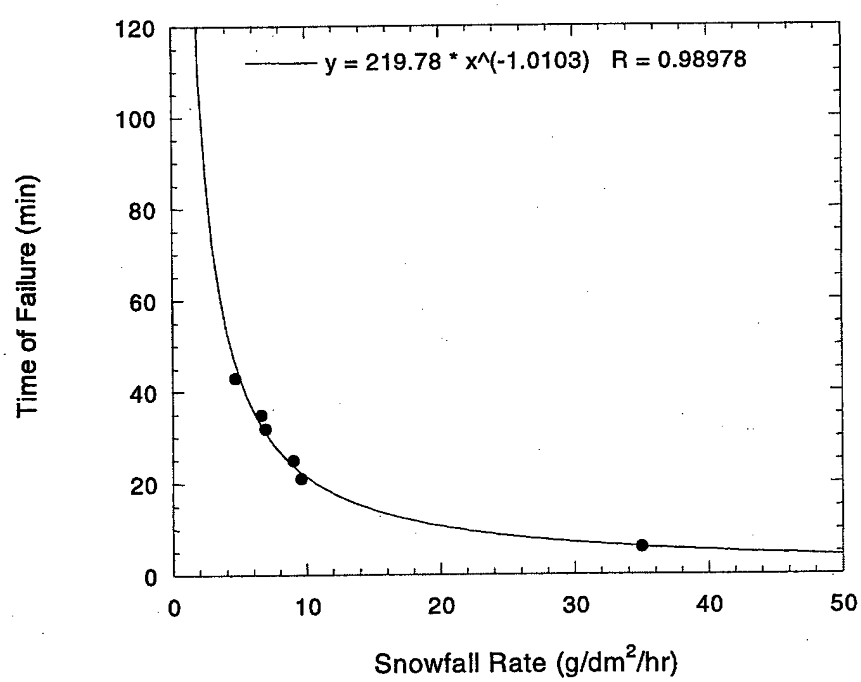

FIGURE 12. HOT VERSUS SNOWFALL RATE—NATURAL SNOW TESTS IN COLD ROOM OF SAFEWING 1957 AT -10°C (PLATE TEMPERATURE FLOATING)

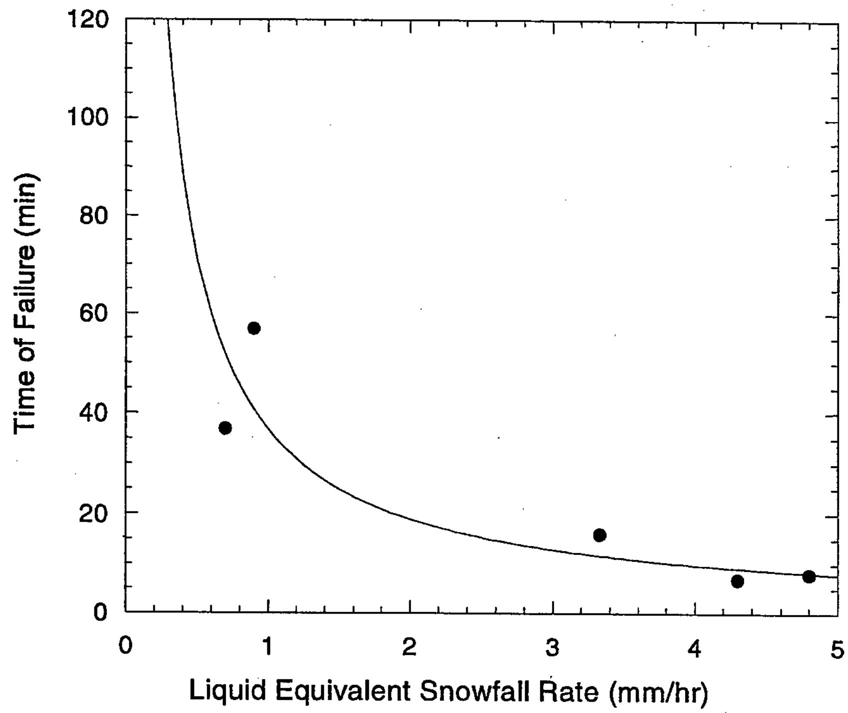

FIGURE 13. HOT VERSUS SNOWFALL RATE—NATURAL SNOW TESTS IN COLD ROOM OF KILFROST ABC-S AT -10°C (PLATE TEMPERATURE FLOATING)

Note that for the data point at 57 minutes for the Kilfrost test was during a case in which the snow decreased at the end of the test, allowing the snow to absorb into the fluid and recover, giving the fluid a longer holdover time.

4. DEICING/ANTI-ICING FLUID TESTS WITH THE IMPROVED ARTIFICIAL SNOW GENERATION SYSTEM.

4.1 RESULTS FROM THE IMPROVED ARTIFICIAL SNOW GENERATION SYSTEM.

To demonstrate the improved system, frosticator panel tests in the cold room using UCAR Ultra+, Kilfrost ABC-S, Safewing MP IV, SPCA AD-480, and Octagon Maxflight, all Type IV anti-icing fluids, were conducted. The fluids were stored in the cold room maintained at -10°C. Tables 2 through 9 give the results of a series of tests with these fluids at -10°C including 75%/25% concentrations. Table 10 gives an example of the rain data recorded on the computer every 6 seconds for the Kilfrost ABC-S, 100% test at 28 $g/dm^2/hr$. Figures 14 through 18 show holdover time versus snowfall rate for these fluids, including a curve fit to the equation holdover time (min) = a S^b, where S is the liquid equivalent snowfall rate in $g/dm^2/hr$ and "a" and "b" are constants of the power law curve fit to the data.

TABLE 2. ARTIFICIAL SNOW TESTS IN COLD ROOM USING ULTRA+, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
128	5.8	-10
55	10.9	-10
25.1	24.1	-10
21	28.5	-10

TABLE 3. ARTIFICIAL SNOW TESTS IN COLD ROOM USING SPCA, AD-480, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
8.2	32.6	-10
134	2.61	-10
36	8.8	-10
73	4.4	-10
12.7	28.3	-10

TABLE 4. ARTIFICIAL SNOW TESTS IN COLD ROOM USING OCTAGON MAXFLIGHT, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
88	5.3	-10
39.3	10	-10
12.7	23	-10
9.4	33.2	-10

TABLE 5. ARTIFICIAL SNOW TESTS IN COLD ROOM USING SAFEWING 1957, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
10.4	36.6	-10
13.5	26	-10
28	10.4	-10
65.9	5.5	-10

TABLE 6. ARTIFICIAL SNOW TESTS IN COLD ROOM USING SAFEWING MP IV, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
8.3	39	-10
15	26	-10
32	11	-10
70	5	-10

TABLE 7. ARTIFICIAL SNOW TESTS IN COLD ROOM USING KILFROST ABC-S, 100%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
95.6	7	-10
48.7	11	-10
17.8	24.9	-10
14.3	28	-10

TABLE 8. ARTIFICIAL SNOW TESTS IN COLD ROOM USING ULTRA+, 75%/25%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
98	2.1	-10
50	4.55	-10
25	9.42	-10
12.6	20.5	-10
8.1	33.5	-10

TABLE 9. ARTIFICIAL SNOW TESTS IN COLD ROOM USING SPCA AD-480, 75%/25%

Holdover Time (min)	Snowfall Rate ($g/dm^2/hr$)	Initial Temperature (°C)
7	20.55	-10
4.9	25.9	-10
23.3	8.3	-10
53.8	4.1	-10
145.2	1.9	-10

TABLE 10. RAW DATA FROM TYPICAL FLUID TEST

Time (min)	Snow Mass (gm)	Total Mass (gm)	Temperature (°C)
0.1	0.6	4272.8	-10.89
0.2	0.93	4273.12	-10.89
0.3	1.07	4273.27	-10.89
0.4	1.23	4273.43	-10.89
0.5	2.08	4274.28	-10.88
0.6	2.85	4275.05	-10.88
0.7	3.65	4275.85	-10.88
0.8	4.4	4276.6	-10.88
0.9	5.28	4277.48	-10.88
1	5.73	4277.93	-10.89
1.1	5.9	4278.1	-10.88
1.2	5.95	4278.15	-10.88
1.3	7.05	4279.25	-10.88
1.4	7.37	4279.57	-10.89
1.5	7.7	4279.9	-11.2
1.6	8.65	4280.85	-11.44
1.7	9.85	4282.05	-11.44
1.8	10.78	4282.98	-11.43
1.9	11.8	4284	-11.43
2	12.65	4284.85	-11.44
2.1	13.53	4285.73	-11.44
2.2	14.48	4286.68	-11.44
2.3	15.28	4287.48	-11.44
2.4	16.2	4288.4	-11.72
2.5	16.95	4289.15	-11.44
2.6	17.85	4290.05	-11.95
2.7	18.9	4291.1	-12.01
2.8	19.65	4291.85	-12
2.9	20.62	4292.82	-12.01
3	21.85	4294.05	-12
3.1	22.8	4295	-12
3.2	23.52	4295.72	-12
3.3	24.45	4296.65	-12
3.4	24.9	4297.1	-12
3.5	25.62	4297.82	-12
3.6	26.47	4298.67	-12.14
3.7	27.35	4299.55	-12.53
3.8	28.4	4300.6	-12.53
3.9	29.32	4301.52	-12.53

TABLE 10. RAW DATA FROM TYPICAL FLUID TEST (Continued)

Time (min)	Snow Mass (gm)	Total Mass (gm)	Temperature (°C)
4	30.1	4302.3	-12.53
4.1	30.93	4303.12	-12.53
4.2	31.9	4304.1	-12.53
4.3	32.95	4305.15	-12.52
4.4	33.53	4305.73	-12.53
4.5	34.32	4306.52	-12.53
4.6	35.2	4307.4	-12.52
4.7	36.07	4308.27	-12.52
4.8	37.12	4309.32	-12.53
4.9	38	4310.2	-12.59
5	38.75	4310.95	-13.08
5.1	39.7	4311.9	-13.07
5.2	40.62	4312.82	-13.07
5.3	41.47	4313.67	-13.08
5.4	42.27	4314.47	-13.07
5.5	43.3	4315.5	-13.08
5.6	43.75	4315.95	-13.07
5.7	44.68	4316.87	-13.08
5.8	45.63	4317.83	-13.07
5.9	46.35	4318.55	-13.07
6	46.83	4319.03	-13.07
6.1	47.72	4319.92	-13.08
6.2	47.95	4320.15	-13.07
6.3	48.43	4320.62	-13.08
6.4	48.3	4320.5	-13.07
6.5	49.13	4321.33	-13.07
6.6	49.48	4321.68	-13.07
6.7	49.73	4321.93	-13.08
6.8	50.18	4322.37	-13.07
6.9	51.15	4323.35	-13.08
7	51.8	4324	-13.59
7.1	52.2	4324.4	-13.59
7.2	52.93	4325.12	-13.37
7.3	53.87	4326.07	-13.22
7.4	54.8	4327	-13.13
7.5	54.97	4327.17	-13.07
7.6	55.9	4328.1	-13.07
7.7	56.55	4328.75	-13.31
7.8	57.1	4329.3	-13.64

TABLE 10. RAW DATA FROM TYPICAL FLUID TEST (Continued)

Time (min)	Snow Mass (gm)	Total Mass (gm)	Temperature (°C)
7.9	57.55	4329.75	-13.43
8	58.05	4330.25	-13.31
8.1	58.37	4330.57	-13.65
8.2	58.7	4330.9	-13.65
8.3	59.15	4331.35	-13.64
8.4	59.57	4331.77	-13.64
8.5	59.83	4332.03	-13.64
8.6	60.2	4332.4	-13.65
8.7	60.98	4333.18	-13.64
8.8	61.82	4334.02	-13.65
8.9	61.9	4334.1	-13.64
9	62.55	4334.75	-13.65
9.1	63.07	4335.27	-13.65
9.2	64.18	4336.37	-13.65
9.3	64.52	4336.72	-13.64
9.4	65	4337.2	-13.64
9.5	65.3	4337.5	-13.64
9.6	66.35	4338.55	-13.65
9.7	66.95	4339.15	-13.65
9.8	67.7	4339.9	-13.65
9.9	68.25	4340.45	-13.64
10	68.7	4340.9	-13.64
10.1	69.5	4341.7	-13.65
10.2	70.05	4342.25	-13.64
10.3	70.48	4342.68	-13.64
10.4	70.95	4343.15	-13.65
10.5	71.43	4343.63	-13.64
10.6	72.27	4344.47	-13.64
10.7	73.28	4345.48	-13.64
10.8	73.75	4345.95	-13.65
10.9	74.62	4346.82	-13.65
11	75.43	4347.62	-13.64
11.1	76.22	4348.42	-13.64
11.2	76.7	4348.9	-13.64
11.3	77.4	4349.6	-13.64
11.4	78.13	4350.33	-13.64
11.5	78.3	4350.5	-13.65
11.6	78.87	4351.07	-13.65
11.7	79.88	4352.08	-13.64

TABLE 10. RAW DATA FROM TYPICAL FLUID TEST (Continued)

Time (min)	Snow Mass (gm)	Total Mass (gm)	Temperature (°C)
11.8	80.8	4353	-13.64
11.9	81.87	4354.07	-13.65
12	82.65	4354.85	-13.65
12.1	83.75	4355.95	-13.64
12.2	84.48	4356.68	-13.63
12.3	85.68	4357.87	-13.64
12.4	86.47	4358.67	-13.64
12.5	87.57	4359.77	-13.64
12.6	88.23	4360.43	-14.11
12.7	89.03	4361.23	-14.18
12.8	90.03	4362.23	-14.18
12.9	90.88	4363.08	-14.18
13	91.62	4363.82	-14.17
13.1	92.95	4365.15	-14.18
13.2	93.68	4365.87	-14.18
13.3	94.87	4367.07	-14.19
13.4	95.53	4367.73	-14.17
13.5	96.45	4368.65	-14.18
13.6	96.77	4368.97	-14.17
13.7	97.68	4369.87	-14.18
13.8	99.05	4371.25	-14.17
13.9	100.43	4372.62	-14.17
14	100.65	4372.85	-14.18
14.1	101.28	4373.48	-14.17
14.2	102.48	4374.68	-14.1
14.2	103	4375.2	-14.17

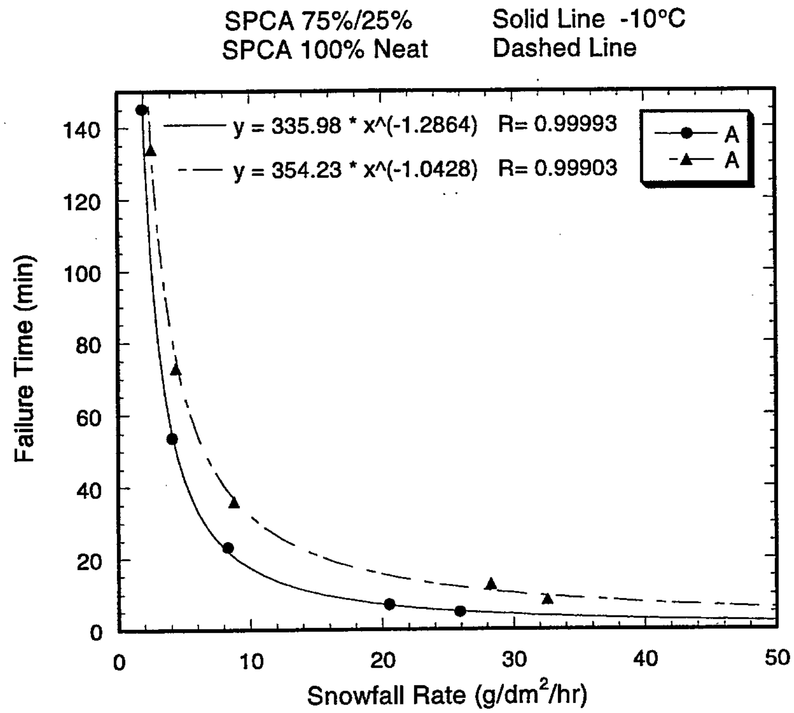

FIGURE 14. HOT VERSUS SNOWFALL RATE—ARTIFICIAL SNOW TESTS IN COLD ROOM OF SPCA AD-480 100% AND 75%/25% AT -10°C (PLATE TEMPERATURE FLOATING)

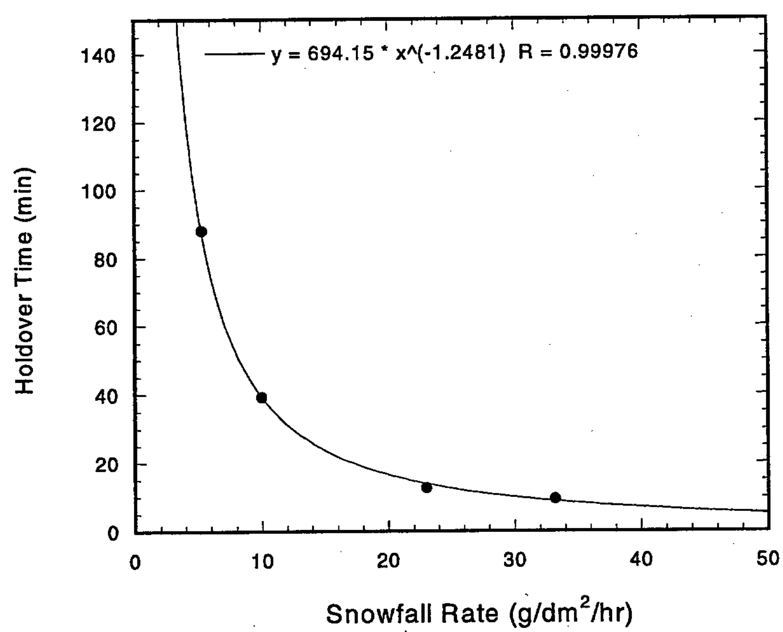

FIGURE 15. HOT VERSUS SNOWFALL RATE—ARTIFICIAL SNOW TESTS IN COLD ROOM OF OCTAGON MAXFLIGHT 100% AT -10°C (PLATE TEMPERATURE FLOATING)

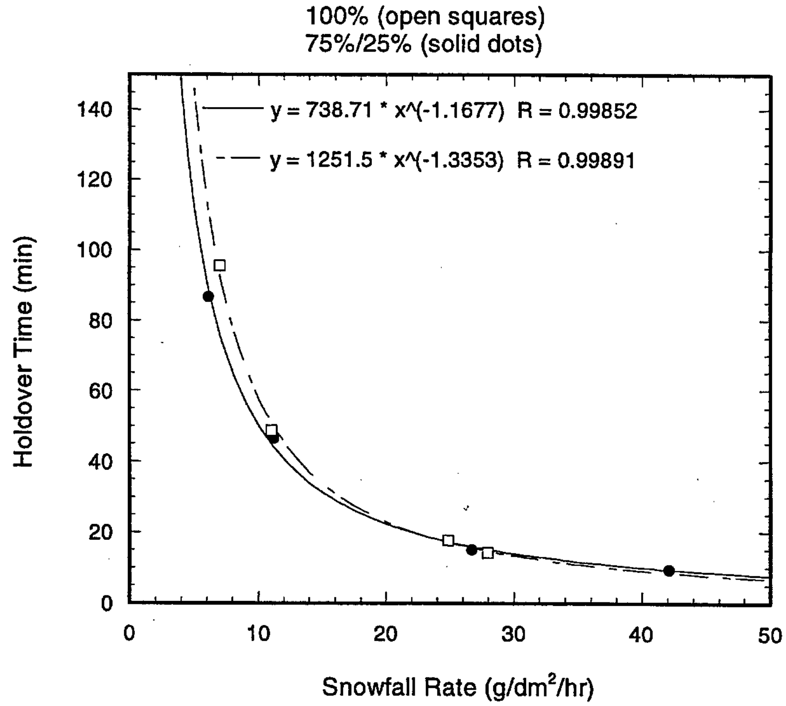

FIGURE 16. HOT VERSUS SNOWFALL RATE—ARTIFICIAL SNOW TESTS IN COLD ROOM OF KILFROST ABC-S 100% AND 75%/25% AT -10°C (PLATE TEMPERATURE FLOATING)

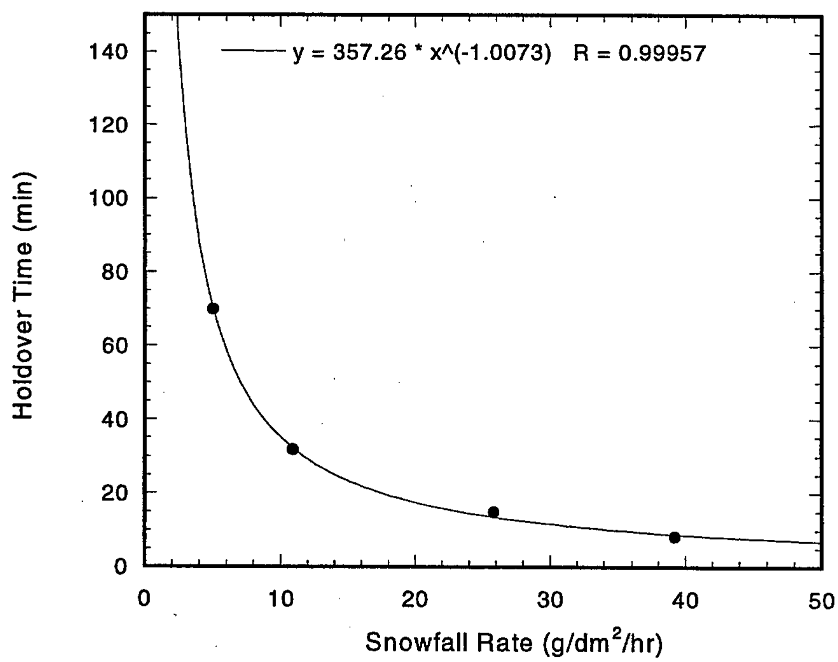

FIGURE 17. HOT VERSUS SNOWFALL RATE—ARTIFICIAL SNOW TESTS IN COLD ROOM OF SAFEWING MP IV 100% AT -10°C (PLATE TEMPERATURE FLOATING)

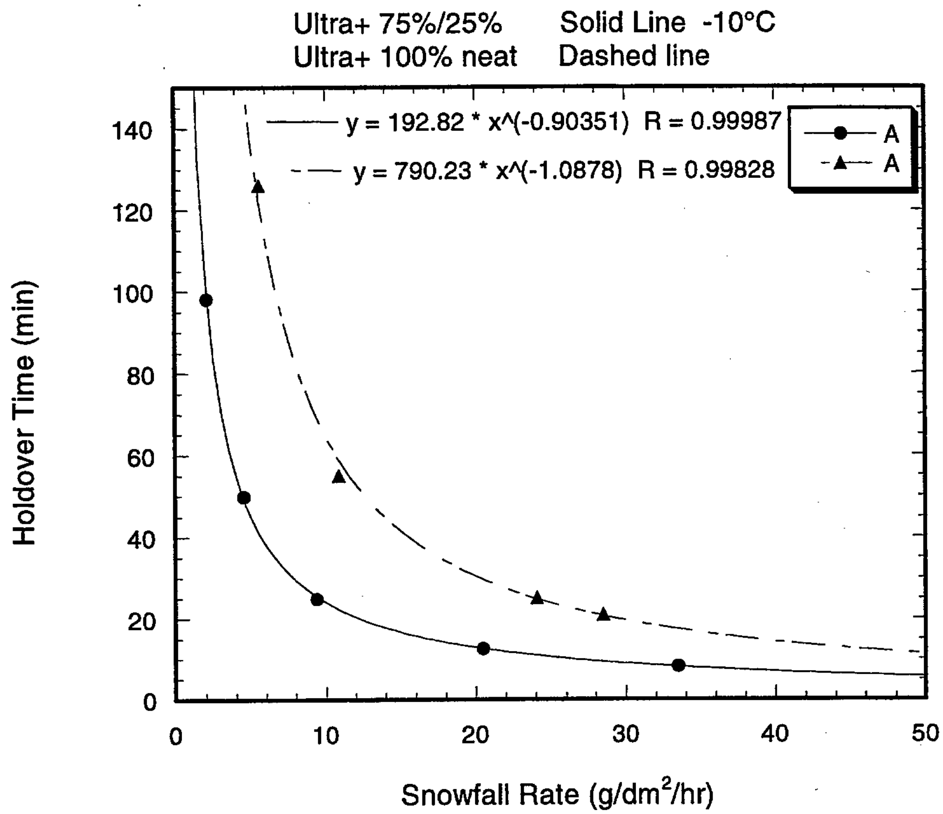

FIGURE 18. HOT VERSUS SNOWFALL RATE—ARTIFICIAL SNOW TESTS IN COLD ROOM OF ULTRA+ 100% AND 75%/25% AT -10°C (PLATE TEMPERATURE FLOATING)

The figures show the expected inverse power law relationship with good correlation (greater than 0.99 in all cases). However, the value of the coefficient "b" is equal to or less than -1.0 in all cases (between -1.0 and -1.3) in contrast to values near -0.8 found by the University of Chicoutimi and APS for both indoor and outdoor tests. Based on results discussed in section 6, we suggest that the smaller values in the current cold room tests may be due to the larger cooling rate of the frosticator plate at high snowfall rates than at lower snowfall rates. Since the outdoor tests are ventilated with wind, the frosticator plates in this case may not cool as much due to the latent heat of melting snow. In addition, the indoor tests conducted by UQAC did not use rates greater than 25 $g/dm^2/hr$. Rates higher than this often result in shorter holdover times due to the large cooling of the plate by latent heat cooling of the snow, decreasing the value of the coefficient "b".

The difference between Kilfrost 100% and 75%/25% fluid was minimal, while the difference between Ultra+ 100% and Ultra 75%/25% was quite large, with holdover time differences of up to 100 minutes at 5 $g/dm^2/hr$ rates. The SPCA fluid displayed maximum differences of only 15 minutes between the 100% and 75%/25% fluid tests.

Figure 19 compares the five 100% fluids and shows that Ultra+ has the longest holdover times, followed by Kilfrost ABC-S, Octagon Maxflight, Safewing MP IV, and SPCA AD-480. Maximum time differences were approximately 60 minutes at rates near 5 g/dm^2/hr.

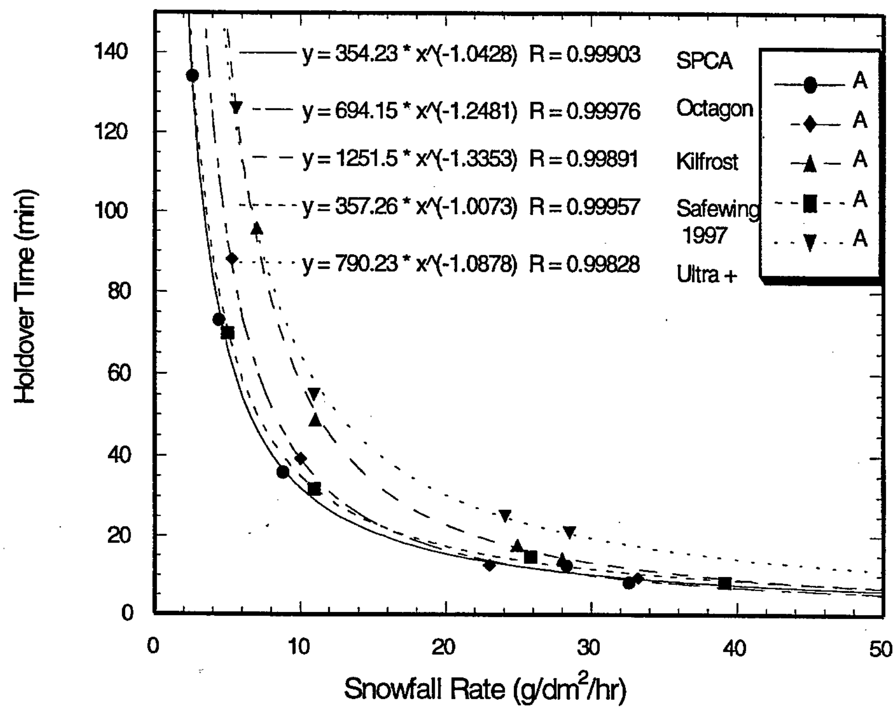

FIGURE 19. COMPARISON OF THE HOT VERSUS SNOWFALL RATE ARTIFICIAL SNOW TESTS OF SPCA AD-480, OCTAGON MAXFLIGHT, KILFROST ABC-S, SAFEWING MP IV, AND ULTRA+ TYPE IV FLUIDS ALL AT 100% CONCENTRATION AND -10°C (PLATE TEMPERATURE FLOATING)

4.2 COMPARISON TO PREVIOUS DATA.

In figure 20, UQAC outdoor and indoor test data for Safewing MP IV neat are compared to the current NCAR indoor tests. Only UQAC outdoor data in the temperature range between -9 and -11°C are plotted in this figure. As can be seen, the current results compare well with the UQAC data for both indoor and outdoor tests of Safewing MP IV. A similar comparison for Ultra+ (figures 21 and 22) shows fairly good agreement except that the NCAR curves have shorter times for high snowfall rates and longer times for low snowfall rates, leading to a smaller value of the power law exponent "b" than in the UQAC outdoor and indoor data as discussed above.

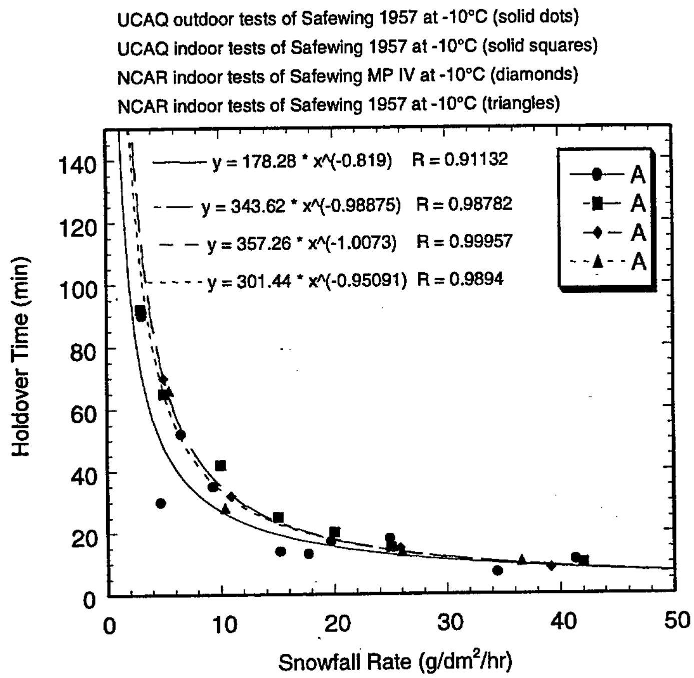

FIGURE 20. COMPARISON OF THE HOT VERSUS SNOWFALL RATE FOR SAFEWING MP IV AND SAFEWING 1957 FOR UCAQ INDOOR AND OUTDOOR TESTS AND NCAR INDOOR TESTS AT -10°C (PLATE TEMPERATURE FLOATING)

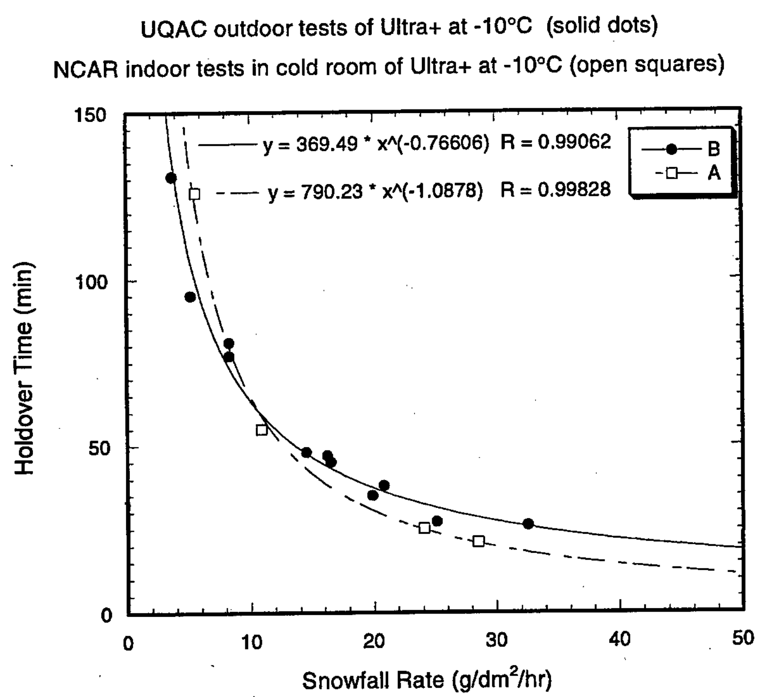

FIGURE 21. UQAC OUTDOOR HOT VERSUS SNOWFALL RATE COMPARED TO NCAR INDOOR HOT VERSUS SNOWFALL RATE FOR ULTRA+ AT -10°C (PLATE TEMPERATURE FLOATING)

UQAC indoor tests of Ultra+ at -10°C (solid dots)
NCAR indoor tests in cold room of Ultra+ at -10°C (open squares)

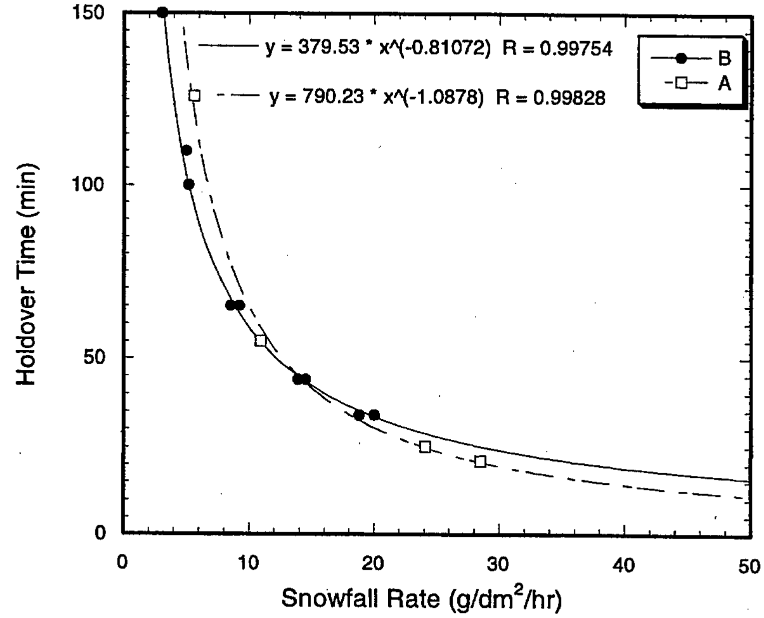

FIGURE 22. UQAC INDOOR HOT VERSUS SNOWFALL RATE COMPARED TO NCAR INDOOR HOT VERSUS SNOWFALL RATE FOR ULTRA+ AT -10°C (PLATE TEMPERATURE FLOATING)

4.3 COMPARISON TO NCAR NATURAL SNOW TESTS IN THE COLD ROOM.

Figures 23 and 24 compare the current NCAR indoor fluid tests of Ultra+ and Safewing MP IV to the natural snow tests discussed in section 3. In this case the NCAR natural snow tests have nearly 50% shorter holdover times than the NCAR and UQAC artificial snow tests and UQAC outdoor tests. Both figures show that the natural snow tests compare favorably to the NCAR artificial snow tests conducted with the original snow machine and the simple frosticator plate. A number of explanations for this behavior can be offered. First, the new frosticator system may not accurately simulate the freestanding frosticator plate used in the natural snow tests. Since the system has side walls to catch any overflow of fluid, natural flow off of the fluid may be slowed down, allowing the fluid to be thicker and therefore extending the holdover time as observed. Another possibility is that the large area silicone heater on the bottom of the frosticator plate changed the heat capacity of the system, possibly preventing the plate from cooling as rapidly as the freestanding plate and leading to a longer holdover time as observed (warmer temperatures lead to longer holdover times in general, Bernadin, 1997). A related possibility is that the frosticator plate in the outdoor testing was prevented from cooling by snow melting due to the rapid heat transfer from the warmer ambient air to the plate by the wind. This would result in longer holdover times as observed and also curves with a smaller exponent since the holdover times associated with the high snowfall rates would be longer. The indoor tests by UQAC may also have been maintained at a warmer temperature than the freestanding plates used in the NCAR indoor cold room tests due to heat transfer through the mounting system. Since the mounting system is metal and in the cold room, it would tend to transfer heat to the frosticator

plate and cause the plate temperature to approach that of the ambient air in the cold room. This last suggestion needs to be investigated further, however.

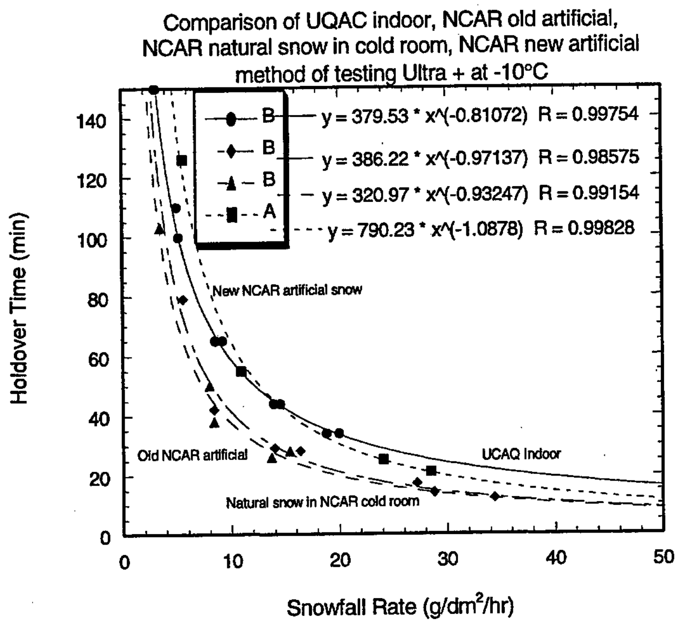

FIGURE 23. COMPARISON OF UQAC INDOOR, NCAR ARTIFICIAL SNOW IN COLD ROOM, AND NCAR ARTIFICIAL SNOW IN COLD ROOM FOR ULTRA+ AT -10°C (PLATE TEMPERATURE FLOATING)

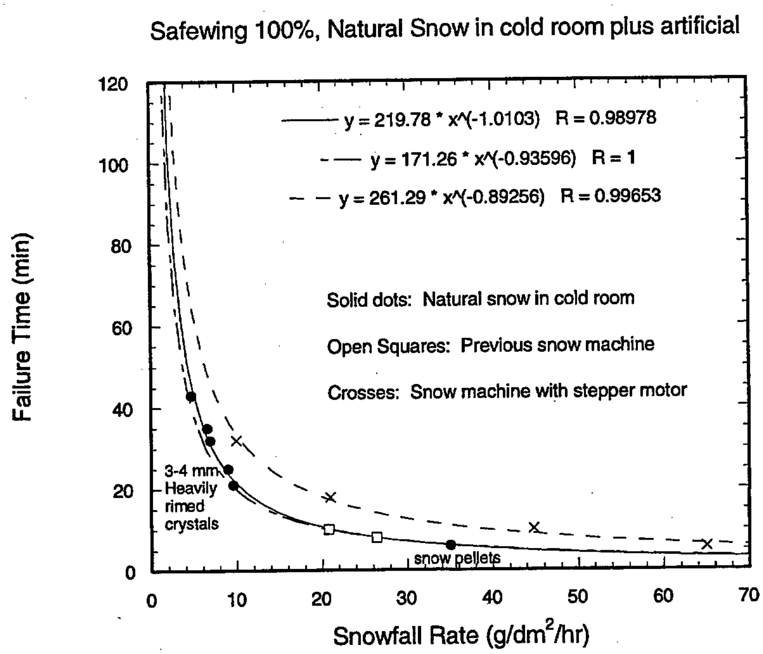

FIGURE 24. COMPARISON OF NATURAL SNOW TESTING OF SAFEWING 1957 TO ARTIFICIAL SNOW TESTING OF SAFEWING MP IV, ALL AT -10°C (PLATE TEMPERATURE FLOATING)

The freestanding NCAR system will likely experience the maximum cooling of all the frosticator plate systems due to (1) the lack of wind in the cold room to warm the plate and (2) the lack of a significant amount of heat transfer through the mounting system due to its freestanding nature, with only one, small attachment point.

Another possibility for these lower holdover times in the natural tests may be with the test procedures of the NCAR natural snow tests. For instance, it may be that the calculated snowfall rate was low due to the indirect method of calculating the snowfall rate. The angle of the plate may also have been too steep despite checking the plate angle prior to every test and resulted in more rapid fluid runoff.

In order to resolve these issues tests are currently being performed with a modified plate on the new frosticator system.

5. THE EFFECT OF SNOWFALL RATE ON FROSTICATOR PLATE TEMPERATURE.

Figure 25 presents the plate temperature as a function of time during fluid tests with Kilfrost ABC-S Type IV fluid for various snowfall rates. The plot shows that the temperature of the plate decreases rapidly by nearly 5°C for high snowfall rates (25 $g/dm^2/hr$), but at lower snowfall rates, the temperature decreases at a slower rate and by a smaller amount. For instance, at a rate of 5 $g/dm^2/hr$, the temperature only decreases by 2°C. The other Type IV fluids used in these tests show similar results. We interpret the observed cooling as due to the latent heat release of the melting snow cooling the fluid and the plate. As the snowfall rate increases, the rate of cooling per unit area of the plate also increases due to more snow per unit time and area melting. The latent heat of melting takes heat out of the plate, causing the plate temperature to decrease rapidly at a rate proportional to the snowfall rate accumulated on the fluid.

Also shown in figure 25 is a theoretical prediction of the rate of cooling of the plate by melting snow assuming a snowfall rate of 25 $g/dm^2/hr$; heat capacity and density of the anti-icing fluid equal to 0.96 cal/gm-K and 1.06 g/cm^3, respectively; heat capacity and density of the aluminum plate equal to 0.218 cal/gm-K and 2.7 g/cm^3, respectively; and that the cooling by melting is equally distributed between the fluid and the aluminum plate. The fluid thickness is taken as 1 mm and the plate thickness as 4.8 mm. The latent heat of melting is taken from Pruppacher and Klett (1997) to be 74.6 cal/gm at -10°C. The only dependence on fluid type is through the heat capacity and density of the fluid, and thus all fluids should show similar behavior.

The initial cooling predicted by the theoretical curve agrees very well with the measured rate of cooling (figure 25). At later times the observed cooling rate is slower than theoretically predicted. This is due to the slower rate at which snow melts when the fluid becomes increasing diluted with melt water, resulting in a lower decrease of temperature. The rate of temperature drop also decreases as a result of the heat transfer from the ambient room air to the plate competing with the cooling due to the melting of snow. This heat transfer rate will be zero at the start of the snowfall due to the air temperature and plate temperature being the same but will increase rapidly as the plate temperature decreases. The good agreement between the initial observed plate cooling rate and the theoretical prediction confirms that the observed plate cooling is most likely due to the latent heat of melting of snow.

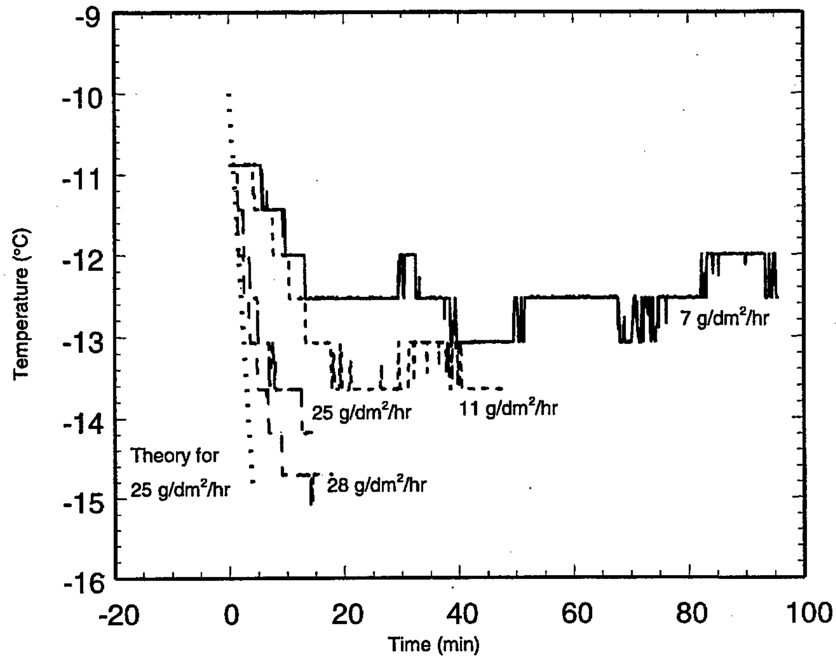

FIGURE 25. TEMPERATURE TIME SERIES OF PLATE TEMPERATURE FROM TESTS OF KILFROST ABC-S 100% AT SNOWFALL RATES OF 7, 11, 25, AND 28 g/dm^2/hr STARTING AT -11°C (PLATE TEMPERATURE FLOATING)

An additional result shown in figure 25 is the temperature plateau reached after the rapid cooling, and then the rapid increase in temperature observed just before failure is called (end of the curve indicates failure point). The plateau region is interpreted as the period in which the cooling due to the latent heat release is balanced by the heating of the plate by the warmer ambient air temperature. When the cooling due to latent heat release stops (fluid can no longer absorb any more snow), then the warmer ambient air starts to warm up the plate. This is precisely the time when fluid failure is called and is consistent with the criteria used to determine fluid failure (snow no longer absorbed into the fluid). Thus, the temperature-time series may be used as an aid in the call of fluid failure. Future tests will investigate this possibility further.

6. THE EFFECT OF PLATE TEMPERATURE ON HOLDOVER TIME.

The results in section 5 show that the latent heat of snow melting cools the plate in proportion to the snowfall rate. In this section we investigate the effect this plate cooling may have on holdover time by comparing tests with the five Type IV fluids conducted under identical conditions except that in one case the temperature of the plate is held constant at -10°C, and in the other case, the temperature is allowed to cool freely at the rate dictated by the snowfall rate as shown in figure 25.

The results show (table 11) that both the failure time and total mass of snow at failure time are 70% to 90% smaller for the free floating plate temperature tests than the tests with a constant-plate temperature of -10°C. As discussed in section 5, the temperature of the plate in the free-floating tests are on average 1 to 3°C colder than the constant-temperature plate tests. Since the

holdover time at colder temperatures is usually shorter than at warmer temperatures (Bernadin et al., 1997), shorter holdover times are expected. The present results show this effect to have a very significant impact on holdover time for a snowfall rate of 25 $g/dm^2/hr$.

TABLE 11. COMPARISON OF CONSTANT PLATE TEMPERATURE FLUID TESTS TO FREE-FLOATING PLATE TEMPERATURE TESTS

Fluid	Concentration (%)	Snowfall Rate ($g/dm^2/hr$)	Temperature Equal to -10°C = Constant or Allowed to Freely Float From an Initial Temperature of -10°C	Total Mass of Snow at Fail Time (gm)	Failure Time (min)
Kilfrost ABC-5	100	26.2	Constant	193	28.5
Kilfrost ABC-5	100	24.9	Free floating	114	17.8
Safewing IV	100	25.9	Constant	168	25.9
Safewing IV	100	26.0	Free floating	90.4	13.5
Octagon Maxflight	100	27.6	Constant	170.2	23.9
Octagon Maxflight	100	23.0	Free floating	75.4	12.7
SPCA	100	15.6	Constant	133.7	33.2
SPCA	100	14.8	Free floating	72.8	19.1
Ultra +	100	24.9	Constant	> 190	> 29.6
Ultra +	100	24.4	Free floating	157.6	25.1

An important question is whether the free-floating plate or the constant-temperature plate is more representative of outdoor tests on a frosticator plate or actual aircraft wing. Since the outdoor tests are usually conducted under windy conditions, the temperature of the plate is constantly being warmed by heat transfer from the air to the plate at a rate that is much faster than the laboratory conditions which have zero wind. In addition, plates are usually attached to test stands made out of metal. These metal stands will be close to the ambient air temperature and will conduct heat into the frosticator plates through their attachment points to the stand. Thus, test plates will tend to be heated through conduction of heat from the stand itself as well as the wind. Actual plate temperatures are likely to lie between ambient air temperature and the cooling rate produced by melting snow. It is planned to conduct additional tests in the future with a variety of outdoor and indoor test stands under snow conditions with wind in order to quantify the effect of wind and heat conduction through the stands on mitigating the cooling of the plate due to snow melting. The above results may help explain some of the variability in previous outdoor test results since different wind speeds and directions will cool the plate differently, leading to a variety of holdover times.

7. ANALYSIS OF TOTAL WATER MASS TO CAUSE FLUID FAILURE.

Figures 26 through 30 provide plots of total snow mass to produce failure as a function of snowfall rate for Ultra+, Octagon Maxflight, SPCA, Kilfrost ABC-S, and Safewing MP IV. The results show that Ultra+ maintains a nearly constant mass for failure as a function of snowfall rate at -10°C, except at 6 $g/dm^2/hr$, similar to the results in our previous report (Rasmussen et al., 1999); Kilfrost and Octagon fluids have decreasing total amounts of snow required to cause failure at the higher snowfall rates; and SPCA and Safewing showing random behavior.

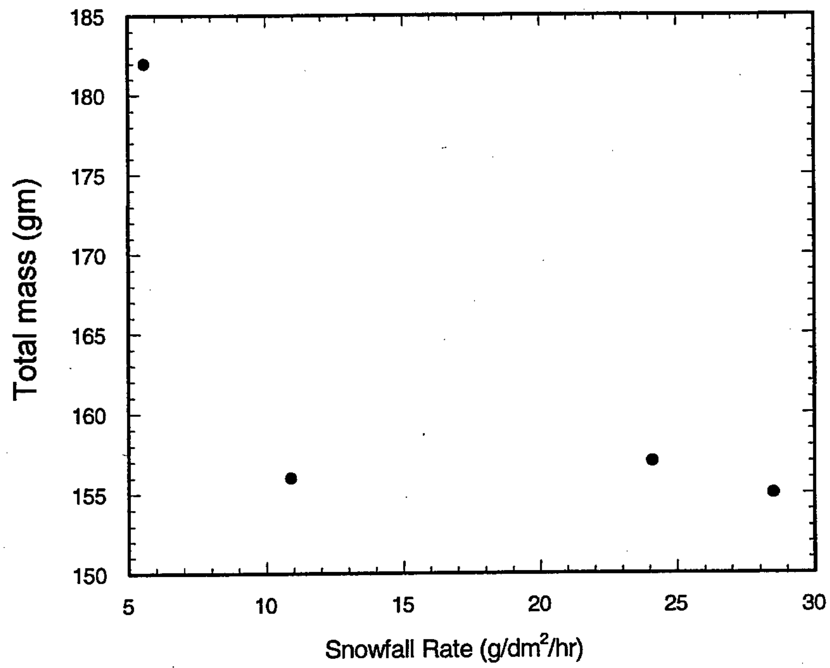

FIGURE 26. TOTAL MASS VERSUS SNOWFALL RATE FOR ARTIFICIAL SNOW TESTS OF ULTRA+ 100% AT -10°C (PLATE TEMPERATURE FLOATING)

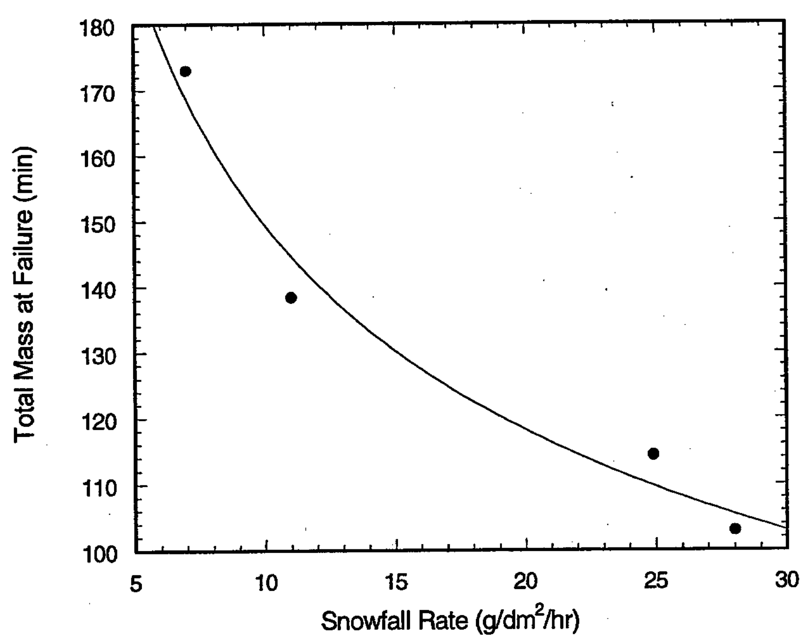

FIGURE 27. TOTAL MASS VERSUS SNOWFALL RATE FOR ARTIFICIAL SNOW TESTS OF KILFROST ABC-S 100% AT -10°C (PLATE TEMPERATURE FLOATING)

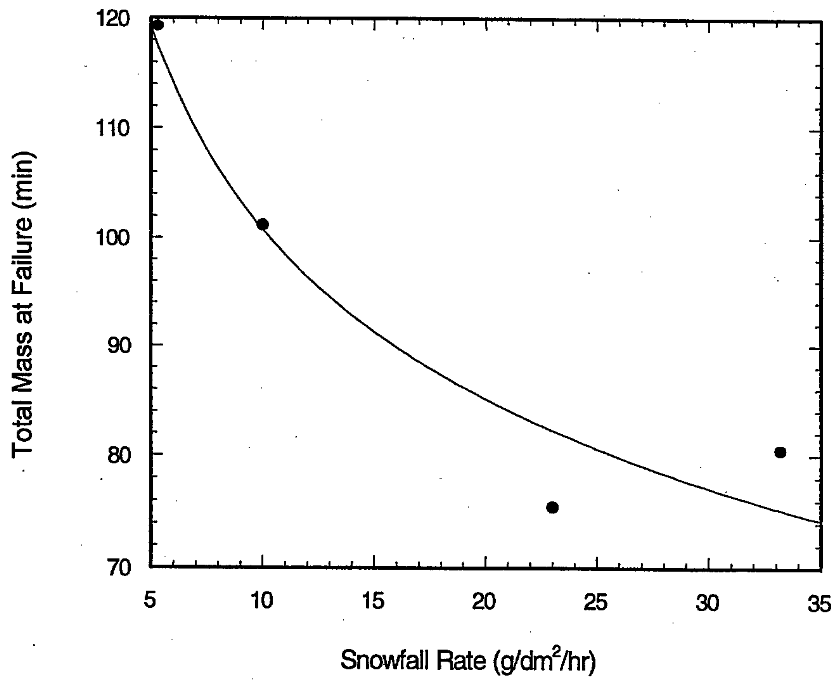

FIGURE 28. TOTAL MASS VERSUS SNOWFALL RATE FOR ARTIFICIAL SNOW TESTS OF OCTAGON MAXFLIGHT 100% AT -10°C (PLATE TEMPERATURE FLOATING)

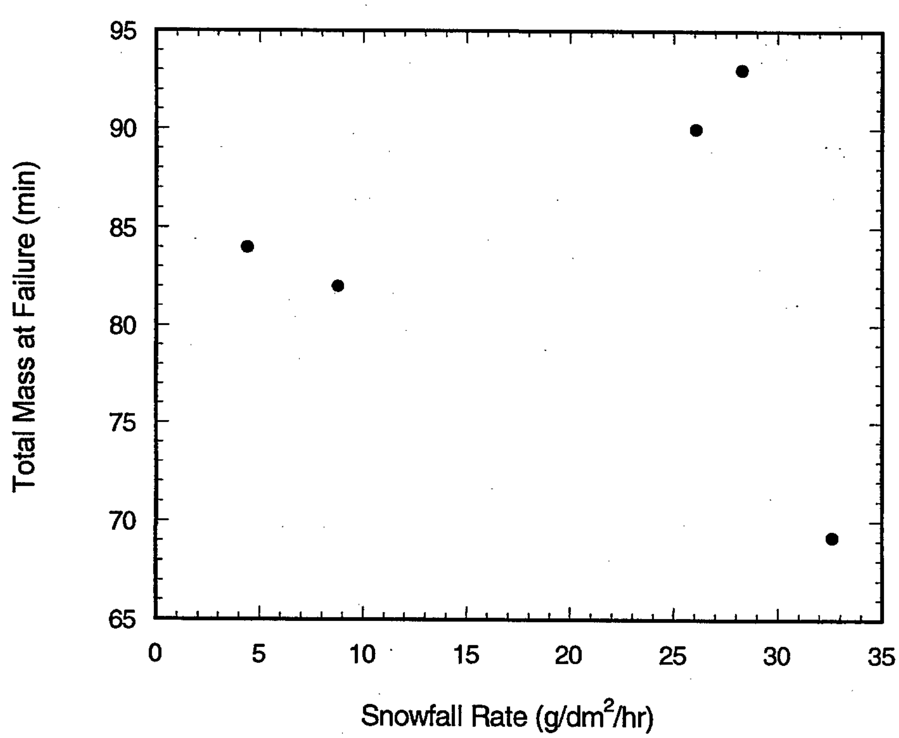

FIGURE 29. TOTAL MASS VERSUS SNOWFALL RATE FOR ARTIFICIAL SNOW TESTS OF SPCA AD-480 100% AT -10°C (PLATE TEMPERATURE FLOATING)

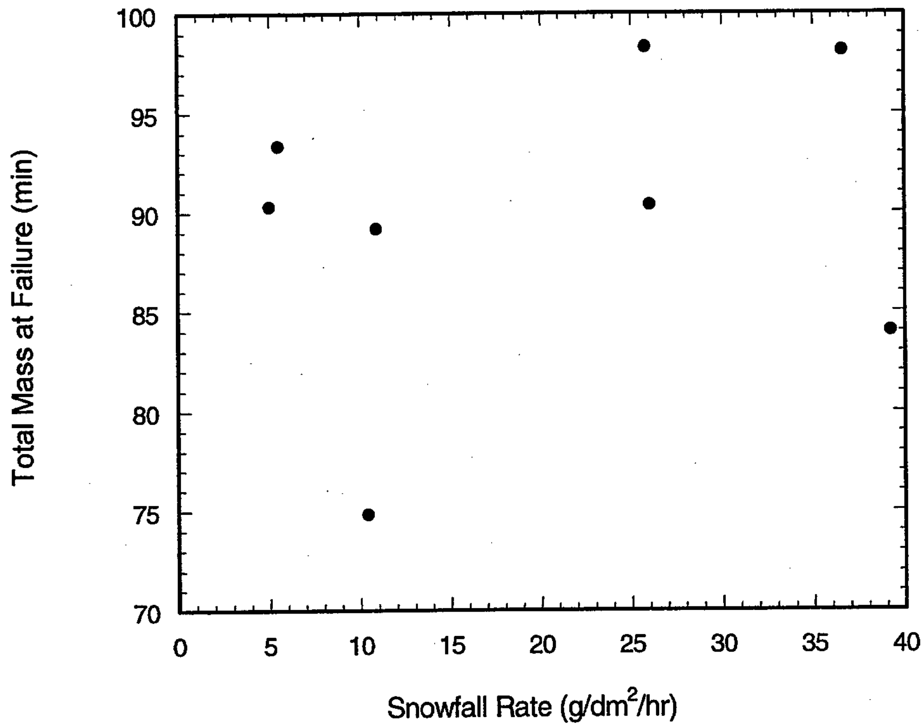

FIGURE 30. TOTAL MASS VERSUS SNOWFALL RATE FOR ARTIFICIAL SNOW TESTS OF SAFEWING MP IV 100% AT -10°C (PLATE TEMPERATURE FLOATING)

A possible explanation for the observed behavior of the total mass as a function of snowfall rate for Ultra+, Kilfrost, and Octagon at -10°C can be given in terms of the effect of melting snow effects on the plate temperature as discussed in sections 5 and 6. Since the holdover times of the fluids usually decrease with decreasing temperature (Bernadin et al., 1999), the holdover time of the fluid with the highest rate will have a proportionately shorter holdover time due to the colder temperature it experiences during its exposure to snow. Similarly, the relatively warm temperatures for the lower snowfall rates result in smaller decreases in the temperature of the plate allowing for a longer holdover time. UQAC and the current results show that Safewing, SPCA, Octagon, and Kilfrost all have shorter holdover times as temperature decreases from -10 to -15°C.

The above translates to less mass and time required for the high snowfall rates to cause fluid failure than for the lower snowfall rates. Ultra+, on the other hand, has nearly no temperature dependence on holdover time between -10 and -15°C (Bernadin et al., 1999), and thus fluid failure is not dependent on temperature but only on the amount of mass. This behavior is corroborated by the data for Ultra + shown in figure 26, which shows that the amount of snow required for Ultra+ to fail is nearly constant as a function of snowfall rate except at 6 g/dm^2/hr. This result was also found by Rasmussen et al. (1997). Thus, the observed trend of decreasing amount of mass to cause failure for increasing snowfall rates observed for some fluids may be partially explained as a result of the lower plate temperatures experienced during the higher snowfall rates, requiring less snow mass for fluid failure.

8. THE EFFECT OF TIME VARYING PRECIPITATION RATES ON HOLDOVER TIME.

The results previously presented assumed that the snowfall rate is constant during the entire test. It is well known, however, that actual snowfall rates are not constant in time but vary significantly on a minute-to-minute basis. This section investigates the possible effect a time varying snowfall rate may have on holdover time by conducting tests in which the snowfall rate is varied. We decided to conduct tests similar to those conducted by UQAC indoor tests in which they deposited snow on test panels for 1 minute and let the panel rest for 2 minutes then repeat the 1 minute on, 2 minutes off application until failure time is reached. Tests were conducted in which the plate temperature was allowed to freely float from an initial temperature of -10°C for the five Type IV fluids mentioned in section 1. A comparison of the total mass at failure time from these time varying tests to the total mass at failure time from the constant rate tests in table 12 was conducted. The results show that the time varying tests could absorb from 1.5 to 2.0 times as much snow as the constant rate tests at the same temperature and snowfall rate (same 1-minute snowfall rate compared to the constant snowfall rate). This translates into a factor of 1.5 to 2.0 longer holdover time as well since the time to accumulate a given amount of snow is obviously related to the total mass of snow.

The above results may possibly be explained by two effects. First, the time varying snowfall has more time to absorb and melt the snow, allowing the fluid to last longer. Thus, the point at which the rate of snow deposition onto the plate exceeds the rate of absorption of snow into the fluid may be reached at an earlier time for the constant-rate conditions than the variable-rate conditions. Second, the temperature of the variable-rate test is on average warmer than the constant-rate test (figure 31) due to the longer time allowed for the heat transfer from the air to the plate and also resulting in a shorter holdover time for the constant-rate condition. Thus, the time variation of snowfall rate is an important consideration in determining holdover time of a fluid, with the holdover time becoming shorter when the rate is more constant. The above results may also help explain some of the variability observed in previous outdoor tests.

9. SUMMARY AND SUGGESTIONS FOR FUTURE WORK.

9.1 SUMMARY.

This report discusses improvements to the NCAR artificial snow generation machine and results of fluid testing with the improved machine. The improvements include (1) improved control of snowfall rate using a digital stepper motor controlled by LabView software running on a notebook PC, (2) development of an integrated frosticator plate/snow mass measuring system that allows the accurate determination of snowfall rate every 1.5 seconds by direct measurement of the weight of snow on the plate being tested, (3) automatic control and recording of the experiment by LabView software running on a notebook PC, (4) temperature sensor in the frosticator plate whose output is recorded every 5 seconds on the PC, (5) addition of a cylindrical guide near the drill bit to allow for an extended length of the ice core for longer experiments, and (6) direct control of the frosticator plate temperature through an area heater controlled by an interface box.

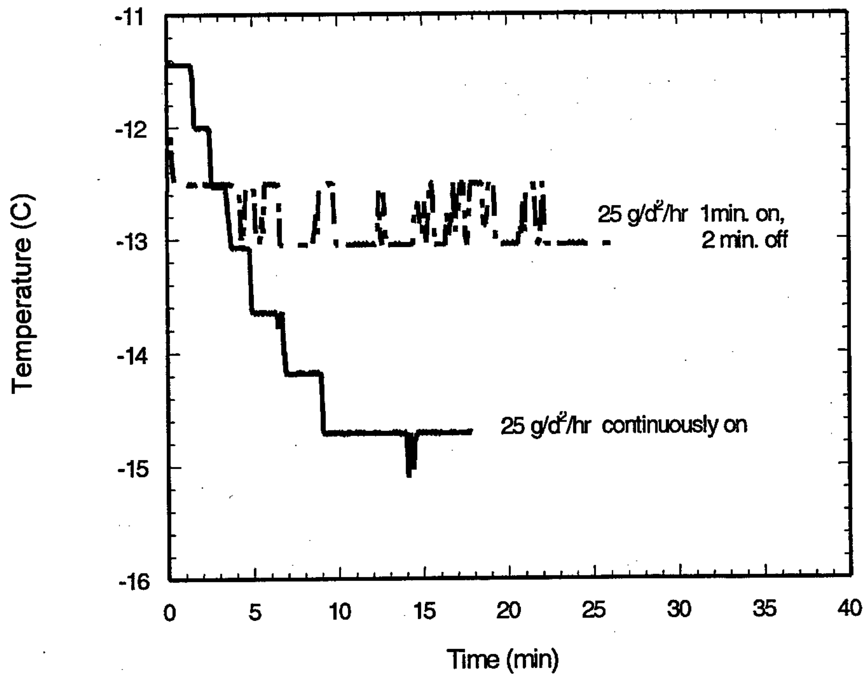

FIGURE 31. TIME SERIES OF PLATE TEMPERATURE FOR THE TIME VARYING SNOWFALL RATE EXPERIMENT WITH THE RATE FOR 1 MINUTE ON AND OFF FOR 2 MINUTES AS COMPARED TO EXPERIMENTS WITH THE RATE EQUAL TO A CONSTANT

TABLE 12. COMPARISON OF TIME VARYING VERSUS CONSTANT SNOWFALL RATES ON HOLDOVER TIME

Fluid	Concentration (%)	Temperature (°C)	Constant or Time-Varying Snowfall Rate	Snowfall Rate ($g/dm^2/hr$)	Total Mass at Failure (gm)
Kilfrost	100	-10.0	Constant	28.0	103
Kilfrost	100	-10.0	On/off	29.6	132.9
Octagon Maxflight	100	-10.0	Constant	33.21	80.5
Octagon Maxflight	100	-10.0	On/off	36.4	170.2
SPCA	100	-10.0	Constant	22.0	70.3
SPCA	100	-10.0	On/off	26.5	105.5
Safewing	100	-10.0	Constant	26.0	90.36
Safewing	100	-10.0	On/off	25.3	113.8
Ultra	100	-10.0	Constant	24.4	157.6
Ultra	100	-10.0	On/off	21.6	> 195.6

This improved machine was used to conduct anti-icing fluid tests on the following Type IV fluids: UCAR Ultra+, Kilfrost ABC-S, Octagon Maxflight, SPCA AD-480, and Clariant Safewing MP IV. The results showed the typical inverse relationship between holdover time and snowfall rate.

Comparison of the results of the Ultra+ and Safewing MP IV testing with indoor and outdoor results from the University of Quebec at Chicoutimi showed good agreement except that the exponent in the current NCAR results had a smaller value of the exponent "b" in the power law relationship, with the value for the NCAR testing falling between -1.0 and -1.3, and the UQAC values between -0.65 and -0.85. The suggested reason for this is the effect of wind warming the outdoor plates, resulting in longer hold times for the higher snowfall rates, which will cause the value of "b" to be larger.

Comparison of the NCAR fluid test results using the artificial snow machine to the natural snow tests conducted in the NCAR cold room using a freestanding frosticator plate showed longer holdover times by nearly a factor of 2 for the artificial snow machine results as compared to the natural snow tests. It is suggested that the natural snow tests using the freestanding frosticator plate allowed for rapid cooling of the snow plate due to snow melting, resulting in shorter hold times due to the colder average temperature of the plate. The frosticator plate used in the artificial snow tests may have had a higher heat capacity due to the heater and mounting on the catchment chamber, causing less cooling and longer holdover times. This suggestion needs to be followed up with further tests however.

An important result from this study is the cooling of the frosticator plate by the release of latent heat during the melting of snow. The plate cooling rate was shown to be proportional to the snowfall rate from both direct plate temperature measurements and theoretical considerations.

Holdover times for Type IV fluids were shown to be significantly shorter when the plate temperature was allowed to cool freely as opposed to being maintained at a constant temperature. This was attributed to the cooler plate temperature for the freely cooling plate as a result of snow melting.

It was also postulated that the heat transfer from the wind and heat conduction from the stand into the frosticator plate may mitigate the effect of cooling by melting snow during natural outdoor tests. This assertion will require future tests to quantify the actual amount of warming that occurs.

The trend of decreasing total snow mass for increasing snowfall rate for Kilfrost and Octagon Type IV fluids may be partially explained by the colder plate temperatures for higher snowfall rates. The nearly constant mass for increasing snowfall rate for Ultra+ may be explained by the lack of temperature dependence on Ultra+ failure time.

Tests with varying snowfall rates showed a factor of 1.5 to 2.0 longer holdover time for fluid failure for nonconstant rates. This result suggests that natural snow conditions are not as severe as the constant snowfall rate conditions tested in the laboratory. Causes for the longer holdover

time were suggested to be (1) the longer time available for the absorption of the melted snow water and (2) the warmer temperatures experienced during the time varying rate tests as compared to the constant-rate tests.

9.2 SUGGESTIONS FOR FUTURE WORK.

9.2.1 Suggested Snow Machine Improvements.

1. Improve the frosticator plate/snow measuring unit by increasing the gap between the plate and the collection unit.

2. Improve the resolution of the temperature sensor from 0.5°C to 0.1°C.

3. Investigate methods to extend the duration of the snow tests by the use of larger-diameter ice cores and larger size drill bits.

4. Investigate methods to increase the snow density and snowflake size distribution by varying the drill speed.

5. Investigate methods to automatically determine the fluid failure point including the use of the time series of the plate temperature.

6. Investigate methods to extend the operation range of the snow machine to temperatures as low as -40°C.

9.2.2 Suggested Future Studies.

1. Investigate the effect of cooling produced by melting snow on the holdover time of deicing/anti-icing fluids.

2. Investigate the use of plate temperature to aid in the determination of fluid failure.

3. Investigate the effect of wind speed on warming the frosticator plate and reducing holdover time.

4. Continue to investigate the effect of time varying snowfall rates on the holdover time of fluids.

5. Perform fluid tests on new fluids at a variety of snowfall rates and temperatures.

6. Perform constant plate temperature fluid tests to investigate the temperature dependence of holdover time for current and new fluids.

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